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International Review Team Report: A Peer Review of the Yucca Mountain IMARC Total System Performance Assessment EPRI Model

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REPORT SUMMARY

Since 1989, EPRI has been conducting independent assessments of the proposed deep geologic repository for the disposal of spent nuclear fuel and high level radioactive waste at Yucca Mountain, Nevada. EPRI pioneered application of the total system performance assessment (TSPA) approach for evaluating performance of geologic repository systems on a probabilistic basis. Along the way, EPRI developed the Integrated Multiple Assumptions and Release Code (IMARC) as its primary analytical tool for TSPA-based evaluations. Over this two-decade time period, IMARC has been periodically revised to reflect the evolving state of knowledge and the changing programmatic and regulatory environment. In 2007, EPRI commissioned an independent technical peer review of IMARC (as Version 9) by an International Review Team (IRT) in order to evaluate the code's technical basis and implementation relative to EPRI's stated goals. With the exception of formatting for publication and addition of a foreword, the final IRT peer-review report is reproduced here in its entirety without alteration or modification.

Background

The governing U.S. Environmental Protection Agency (EPA) standards and Nuclear Regulatory Commission (NRC) regulations for the proposed Yucca Mountain repository are probability-based. This probabilistic nature and the long time frames associated with geologic disposal led to development of the TSPA methodology for demonstrating repository performance and regulatory compliance. As part of its preparation for a license application for repository construction, the U.S. Department of Energy (DOE), the licensee, has developed a comprehensive and highly complex TSPA program. The NRC, the designated regulator for this facility, has done likewise in support of its license review. As an independent third party, EPRI developed the IMARC code primarily to provide technical insights into the most risk-important features, events, and processes affecting overall repository performance and regulatory compliance. The code also provides a credible, independent, technically defensible TSPA capability to evaluate DOE and NRC models and parameters. Implementation of IMARC is intended to reflect a reasonable or best-estimate philosophy, consistent with the EPA standard codified in 40 CFR 197.14, as opposed to bounding or worst-case approaches. IMARC is not intended to duplicate the DOE and NRC codes in rigor and depth.

Objectives

The intent of this peer review is to provide an independent evaluation of EPRI's TSPA code, IMARC, in light of EPRI's role as an independent third party to the Yucca Mountain process. Specifically, the IRT was tasked with determining if IMARC is "fit for purpose" by

- Determining if the overall approach is reasonable, viable, and consistent with the goals of the EPRI Yucca Mountain research program

- Identifying areas, if any, where the code or its subcomponents would benefit from changes to better achieve the goals of the EPRI program
- Identifying assumptions and input data that warrant further review and possible revision
- Confirming the application of the reasonable/best estimate approach
- Evaluating the adequacy of IMARC code documentation in EPRI reports

Approach

The three-member IRT was assembled based on subject matter expertise, independence from the Yucca Mountain program, direct experience with performance assessments and geologic repository systems, and availability. The team was provided information in the form of documentation, presentations, and verbal discussions via three face-to-face meetings and a number of teleconferences with appropriate members of the EPRI research team.

Results

The IRT found that the IMARC code provides an integrated presentation of the total repository system and captures the main processes and their interactions for a repository located at Yucca Mountain, Nevada. The IRT concurred that IMARC is "fit for purpose" in that it provides a risk-based methodology for integrating information from various disciplines affecting long-term repository performance. The IRT found that the models and databases in the IMARC 9 code conformed to performance analyses that are consistent with a "reasonable expectation" approach per the EPA's Yucca Mountain standards. IMARC was also judged to be a well-integrated performance assessment tool, which focuses on those processes that could affect the long-term safety and regulatory compliance of a repository located at Yucca Mountain. Opportunities for expanding and refining the capabilities of the IMARC code were also identified in the IRT review. The IRT strongly supported verification and code intercomparisons to gain additional insights into the various assumptions and modeling approaches and for enhancing the scientific credibility of the model. The IRT review called attention to a number of areas in which model documentation could be improved.

EPRI Perspective

This peer review provides an important independent technical assessment of the IMARC code, parameters, and implementation in the context of EPRI's role as an independent third party evaluating the performance of the proposed Yucca Mountain repository system. EPRI response to comments and recommendations from the IRT is provided in a separate report documenting the resulting IMARC code revision, Version 10: *EPRI Yucca Mountain Total System Performance Assessment Code (IMARC) Version 10: Model Description and Analyses* (EPRI 1018712, 2009).

Keywords

Yucca Mountain
High Level Radioactive Waste
Spent Nuclear Fuel
Total System Performance Assessment (TSPA)
IMARC Peer Review

LIST OF ACRONYMS

BCDF	Biosphere Dose Conversion Factor
DS	Drip Shield
EBS	Engineered Barrier System
EBSCOM	Engineered Barriers System Corrosion Model
EPRI	Electric Power Research Institute
FEPs	Features, Evens and Processes
GC	General Corrosion
HIC	Hydrogen-Induced-Cracking
IAEA	International Atomic Energy Agency
IRF	Instant Release Fraction
IRT	International Review Team
ISAM	Improvement of Safety Assessment Methodologies
LC	Localized Corrosion
MC	Monte Carlo
MIC	Microbial Influenced Corrosion
pdf	Parameter Distribution Function
RMEI	Reasonably Maximally Exposed Individual
SCC	Stress Corrosion Cracking
SZ	Saturated Zone
TAQ	Temperature for formation of Aqueous Phase
TMIC	Threshold temperature for MIC
TSPA	Total System Performance Assessments
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
US NRC	United States Nuclear Regulatory Commission
UZ	Unsaturated Zone
WP	Waste Package

FORWARD

In 2007, EPRI commissioned an independent peer review of EPRI's most recent IMARC code version for total system performance assessment (TSPA).[1] An International Review Team (IRT) conducted its review during late-2007 and early-2008 following the guidelines and protocols of the International Atomic Energy Agency's Improvements on Safety Assessment Methodology (ISAM). This ISAM methodology was adopted as a review framework to ensure a systematic review of the IMARC 9 draft report, as well as to conform to international standards.

The following report provides the findings of the IRT as received by EPRI without alteration or modification, except for formatting. Publication of this report is followed by the EPRI IMARC 10 model report, which includes EPRI's response to the IRT review and documents changes to the IMARC code resulting from the IRT findings and recommendations (EPRI report 1018712, *EPRI Yucca Mountain Total System Performance Assessment Code (IMARC) Version 10: Model Description and Analyses*, 2009).

Drawing on more than 20 years of experience in the field of geologic repository performance assessment, EPRI and its principal research contractor, Monitor Scientific LLC, assembled a list of candidates based on the following areas of expertise required for the review:

- Climate/infiltration/seepage,
- Containment,
- Source-term release,
- Unsaturated and saturated zone flow and transport,
- Dose modeling, and
- QA of code development and performance assessment related modeling.

In addition, candidates were screened on the basis of independence with respect to the Yucca Mountain Project, direct experience in conducting performance assessments associated with geologic repositories, and availability with respect to the program schedule. A chairperson was selected jointly by Monitor Scientific and EPRI and served to assist Monitor Scientific with the selection of the remaining team members. Resource constraints, conflict of interest concerns, and logistical considerations limited the team to three members.

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[1] The IMARC code version reviewed by the IRT was interim version IMARC 9, which represented an incremental revision of IMARC 8 (EPRI report 1011813: *EPRI Yucca Mountain Total System Performance Assessment Code (IMARC) Version 8: Model Description*, 2005). The relatively minor revisions comprised changes in input data exclusively; no changes were made to the IMARC 8 conceptual or numerical models.

Monitor Scientific served as facilitator during the review for coordinating contact between the IRT and the EPRI research team (EPRI staff, Monitor staff, and other IMARC experts), organizing teleconference calls to enable the reviewers to ask questions and receive explanations directly from appropriate EPRI team experts, and providing additional supporting documentation as requested. Monitor Scientific developed and provided documentation of the current status of the IMARC code to the IRT. In addition, copies of all available historical documentation of the code and its development were made available to the review team. The review team members were also given the opportunity to examine the code in person at Monitor Scientific's Denver offices.

The review process was initiated with a kickoff meeting on September 6 - 7, 2007, among EPRI, the EPRI research team (Monitor Scientific and its subcontractors) and the IRT members during which an overview of the IMARC code and its history was given. The IRT also met separately at that time to establish review subject assignments and the process for the review (see Appendix B). Throughout the review, the IRT members communicated amongst themselves by teleconference as needed. A second face-to-face meeting was held on October 22 – 24, 2007, to permit the IRT to meet again with appropriate EPRI research team members and to receive further clarifications and input from IMARC experts.

After completion and documentation of initial reviews by IRT members, the peer review team chairperson compiled and integrated the review comments into an executive summary, checking the comments for relevance and consistency with respect to the established terms of reference (Appendix B). Any disputes arising with regard to the disposition of comments by the chairperson resulted in written exceptions appended to the reviewer's comments. This integrated review document was then reviewed by all IRT members for accuracy and consistency. The chairperson made corrections as necessary and then distributed the initial draft review document to Monitor Scientific and EPRI in December 2007. A final face-to-face meeting between the IRT, Monitor Scientific and EPRI was held on January 15, 2008, to resolve questions and comments requiring further clarification. A final consensus document was then prepared by the chairperson in consultation with the other IRT members and submitted to Monitor Scientific and EPRI in April 2008.

A PEER REVIEW
OF THE
YUCCA MOUNTAIN
IMARC TOTAL SYSTEM PERFORMANCE ASSESSMENT EPRI MODEL

Prepared for:

The Electric Power Research Institute

Prepared by:

International Review Team

April 2008

EXECUTIVE SUMMARY

ES1 Background

The “Electric Power Research Institute” (EPRI) has conducted “Total System Performance Assessments” (TSPAs) of the Yucca Mountain repository to gain insight into important repository system features, events and processes with respect to estimates of radiation dose to a hypothetical “reasonably maximally exposed individual” (RMEI) living downstream of the repository, as defined by U.S. EPA (40 CFR197). The EPRI TSPA code, IMARC, was designed to provide an assessment of processes which are likely to occur and their impact on the radiation dose estimate to the RMEI. The focus of the EPRI TSPAs is on the disposal of spent commercial fuel.

This report presents the results of a peer review of EPRI’s IMARC methodology for TSPA, keeping in mind the EPRI TSPA objective. This review is the outcome of the work of an international team of three members, over a period of about three months. The main focus of the review has been a draft of the IMARC 9 model documentation (EPRI 2007), with a partial review of key supporting documents. Given the time constraints, the IRT (International Review Team) was primarily concerned with high level features of the model rather than with details.

The International Atomic Energy Agency’s (IAEA’s) Improvements on Safety Assessment Methodologies (ISAM) methodology (originally developed for near-surface disposal facilities) was adopted as a framework for the peer review to ensure a systematic review of the IMARC 9 draft report by the IRT. The review therefore followed the steps outlined by the ISAM methodology as follows:

ES2 Assessment Context

EPRI notes that U.S. NRC 40 CFR 197 and 10 CFR 63 call for the performance of analyses that are consistent with a “reasonable expectation” philosophy as opposed to a “most conservative” philosophy. The IRT considers that EPRI has adopted an appropriate assessment context according to its role and that EPRI’s implementation of the IMARC code is consistent with the “reasonable expectation” philosophy and the applicable regulations.

ES3 System Description

The IMARC 9 documentation focuses on the IMARC model and does not provide a detailed description of the disposal system and its components, beyond those necessary to understand what the model is seeking to represent. EPRI’s reliance on information regarding the disposal system characteristics published by the U.S. DOE and others is appropriate, but the IRT considers that the current IMARC 9 documentation could be improved by providing more detail on the disposal system and its (geometrical) conceptualization.

ES4 Development and Justification of Scenarios

EPRI's development of IMARC has tracked the evolution of Yucca Mountain regulations, disposal system design, and conceptual understanding of the proposed repository over the years and current emphasis is on three primary scenario variants:

- A nominal scenario, which comprises the features, events and processes (FEPs) that are expected to occur (as opposed to unlikely FEPs), including certain seismic effects.
- An igneous intrusive scenario.
- An igneous extrusive scenario.

The igneous intrusive scenario has been addressed using IMARC in EPRI (2005). The FEPs associated with the igneous extrusive scenario are very different than those implemented in IMARC, and as a result, this scenario has been evaluated using a different modeling approach.

The inadvertent human intrusion scenario established in 10 CFR Part 63 has not been addressed in IMARC or in other EPRI analyses for two reasons:

- 10 CFR Part 63 prescribes a stylized examination of inadvertent human intrusion manner and does not permit significant alternative viewpoints.
- Inadvertent human intrusion scenarios are not expected to be significant in licensing of the Yucca Mountain repository (U.S. DOE/OCRWM, 2000).

In general terms, EPRI has followed an approach to the identification and justification of scenarios and models that is largely based on the regulatory context for the assessment of a repository at Yucca Mountain, coupled with expert judgement regarding which FEPs should be included (or excluded) from TSPA models and sub-models. The IRT considers that the EPRI approach to the identification and justification of scenarios is appropriate, given EPRI's assessment context and its focus on developing a model that provides a reasonable representation of expected system behaviour. The focus of the IRT's review has been on the nominal scenario. It is proposed that a future review will address EPRI's application of IMARC to alternative credible scenarios such as igneous events, rockfall and expanded capacity of the repository.

Consistent with its objectives and priorities EPRI has not conducted a formal FEPs audit to confirm that all relevant FEPs are appropriately accounted for (or eliminated from) its chosen scenarios and models. A systematic formal audit of FEPs would be expected of the U.S. DOE as potential implementer of the repository at Yucca Mountain. However, it is recommended that EPRI reviews the U.S. DOE FEPs documentation for comparison with its assessment models.

ES5 Model Formulation and Implementation

EPRI's approach to model formulation and implementation has been to contract a team of experts, collectively possessing expertise in a wide variety of relevant disciplines. Individuals from this team have been given responsibility for developing detailed conceptual models and software to represent various parts of the disposal system, according to their areas of expertise. A lead contracting organisation (Monitor Scientific) maintains and runs the IMARC code, which provides a TSPA capability based on the various detailed models or their outputs.

The IRT considers that the model formulation process is reasonable; it relies on 'cross-review' of work by other members of the assessment team and by peer reviewers, as well as controls over the quality of the work and software development. The IRT suggests that EPRI should consider reviewing and adopting centralised methods for recording and controlling changes to model assumptions, data and parameter values, and for making these readily available across the expert team (e.g. the Vignette knowledge management system used by the Belgian Agency for Radioactive Waste). Overall, the model formulation process followed by EPRI results in a very efficient, high quality, well integrated and "fit for purpose" TSPA model.

The following paragraphs comment on the IMARC 9 component models.

ES5.1 Climate Change

Climate and climate change are likely to be important controls on the amount of water that flows through Yucca Mountain and may, thus, affect repository system performance. Over extremely long periods, major changes in the global climate could occur, for example, leading to a transition to a glacial climate.

EPRI's approach to representing climate and climate change in IMARC 9 is generally clear, although the terms 'present-day interglacial', 'greenhouse', and 'full glacial maximum' should be clearly defined and their use made more consistent in the next revision of the IMARC documentation. Perhaps more importantly the draft IMARC 9 report does not present the rationale for the assumed durations of the first two climate states.

Nevertheless, the IRT considers that the overall EPRI approach to representing climate change in IMARC 9 is generally consistent with the proposed regulations. An approximation is however introduced because IMARC 9 represents the U.S. NRC proposed log-uniform distribution for infiltration rate using a three-point discrete distribution) (see also ES5.2 and ES6.2).

The IRT recommends that EPRI incorporates a discussion of the potential effects of global warming into the document.

ES5.2 Infiltration

Net infiltration is a hydrologic parameter that controls the rate of deep percolation, radionuclide transport, groundwater recharge and groundwater seepage into the repository.

Net infiltration is largely dependent on the climatic conditions. It is therefore appropriate that the net infiltration modelling in IMARC is climate dependent. Furthermore, the assignment of low, moderate and high values to the net infiltration event-tree branches is a reasonable approach for capturing uncertainty and variability in this parameter value, and is commensurate with the available meteorological data.

In addition, this simple approach is justified because in the very long-term, i.e. beyond 10^4 years (when infiltration could affect the dose risk from the repository, by affecting radionuclide transport from Engineered Barriers (EBS) which are expected to gradually fail in the long-term) the infiltration rate in the TSPA has been proposed by U.S. NRC.

Specific suggestions for improved documentation of the infiltration model include:

- addition of a water balance diagram;
- explanation of the coupling between infiltration, percolation and seepage in IMARC 9;
- clarification of the effect (or lack thereof) of infiltration on EBS degradation rates;
- addition of the model equations which use the infiltration rates (or reference to other sections where these may appear);
- reference to the literature source(s) where the model and model parameters are derived.

As IMARC is periodically updated to reflect scientific progress, the IRT suggests that it would be beneficial to use the IMARC 9 tool to evaluate the dose/risk implications of uncertainties related to selecting the (EPRI, 1998) range of net infiltration rates versus other recent work (e.g., Faybishenko, 2007) or other recent assessments. Since infiltration rates affect percolation through the Unsaturated Zone (UZ) and groundwater recharge, it would also be useful to carry out a sensitivity analysis to evaluate how sensitive the UZ and Saturated Zone (SZ) radionuclide transport are to uncertainty in the net infiltration rate over the first ten thousand years after disposal.

ES5.3 Seepage

Seepage, i.e. free water flow, into the disposal drift, is a function of the infiltration and is affected by the capillary barrier of the open drift, which at small infiltration rates will allow the water to flow around the drift without any seepage into it. Furthermore, the heterogeneous nature of the fractured tuff implies that the average net infiltration is focused into some areas and away from other areas.

The IMARC 9 seepage model is based on a critical assessment of U.S. DOE work in this area and appears to be state-of-the-art. The EPRI model seems justified and not unnecessarily conservative. However, a few remarks are warranted regarding clarity of the documentation.

Initially it was not clear how the different seepage assessments made by U.S. DOE had been used in justifying EPRI's model. Only after discussions with the IMARC team, did it become evident that the model justification is based on the critical review of U.S. DOE reports presented in (EPRI 2000).

There is a need to expand the justification for omitting episodic flows. The fracture asperity argument presented in EPRI (2002a) is plausible, but does not provide sufficient evidence. The argument would be much enhanced if combined with observations from the existing drift at Yucca Mountain.

The handling of seepage during high sub-boiling temperatures would benefit from additional discussion. The IRT agrees that it is reasonable to omit this aspect from the model, because the containment model is not coupled to the seepage model, and because containment is generally long-term (i.e. it is functioning well into the temperate region when the IMARC seepage model becomes valid). However, should either of these conditions become invalid (e.g. by future updates of IMARC 9 or by new data on containment times), then it would be necessary to revisit the seepage model. The IRT, thus, recommends that this, as well as other critical assumptions, be clearly documented at an overview level.

ES5.4 Containment

Containment failure (i.e. a breach of the engineered barriers) would lead to the release of radionuclides from the wasteform. Containment failure encompasses several aspects including: corrosion processes, undetected initial defects and geotechnical issues.

ES5.4.1 Corrosion Aspects

IMARC's EBSCOM code assesses the rate of failure of the components of the engineered barriers system. It includes models for the rate of failure of:

- The cladding;
- The titanium Drip Shield (DS);
- The Alloy 22 Waste Package Shell (WP) and Waste Package Closure welds.

<u>The cladding failure model</u> in IMARC 9 addresses the following modes of failure:

- Initial cladding failure;
- Localized corrosion (LC) – this process (e.g. pitting in oxidizing saline conditions), is acknowledged in the text but not taken explicitly into account because the consequences of pitting failures are not expected to be significant, since the apertures are expected to be small and at least partially blocked by corrosion products;
- General corrosion (GC for wet and dry conditions);
- Hydride reorientation – this process is neglected because cladding temperatures for higher burn-up spent fuels during drying operations (prior to transfer from pool to dry storage) are limited to 400ºC. This operational limit ensures that little or no hydride reorientation should occur.

The IRT concurs that relevant failure mechanisms are addressed in the IMARC 9 description of the cladding failure model and supports the consideration of the cladding as part of the EBS in

IMARC 9. Furthermore, the IRT concurs with the argument that pitting corrosion is unlikely to lead to a major exposure of fuel for dissolution. However, the IRT recommends that EPRI adds a discussion providing rationale for this argument and showing that neglecting this process will not have a significant impact on the estimated dose.

The drip shield (DS) failure model in IMARC 9 addresses the following modes of failure:

- GC – This is represented by a temperature dependent Arrhenius expression. The modelling keeps track of the fraction of GC of the drip shield supported by the cathodic reduction of O_2, which does not result in hydrogen absorption. This is important because it affects the probability of drip-shield failure by Hydrogen-Induced-Cracking (HIC).
- Hydrogen Induced Cracking (HIC) – The corrosion of Ti by H_2O produces hydrogen atoms that can be absorbed by the DS and lead to hydrogen-induced cracking. Failure of the DS by HIC can occur once the absorbed hydrogen concentration reaches a critical value.

The IRT agrees that relevant modes of failure are addressed in the IMARC 9 description of DS failure. Furthermore, the IRT concurs with the modelling of these corrosion processes. In particular the IRT supports the recent modification in the HIC model which now takes into account the release of absorbed H as the Ti matrix corrodes and converts to TiO_2.

The waste package (WP) failure model in IMARC 9 addresses the following modes of failure:

- GC – this is represented by a temperature dependent Arhenius relationship. No enhancement factor is included to account for thermal aging. A factor is used to represent reduction in the tensile stress that would reduce the rate of GC for the laser-peened closure weld on the outer lid.
- LC – this is represented through initiation (under specific conditions) and a rate of propagation. If LC initiates, it is assumed to continue to propagate at a time dependent and temperature-dependent rate. The rate of propagation is assumed to decrease with time, essentially stifling LC growth after a certain period of time.
- Microbial Influenced Corrosion (MIC) – The WP is susceptible to MIC when the temperature is below a threshold temperature. Therefore, MIC of the WP is potentially important in the long-term once environmental conditions in the drift have ameliorated sufficiently to allow microbial activity. One of the major stressors for microbial activity in the repository is the general lack of water, characterized by the low % Relative Humidity (RH) in the drift. The time dependence of the %RH in the drifts is not explicitly included in EBSCOM but, as RH and temperature are closely linked, the conditions for the onset of microbial activity in the repository following the thermal pulse are defined by a threshold temperature. Once active, MIC is represented in IMARC 9 through two factors that enhance the rates of GC and LC.
- Stress Corrosion Cracking (SCC) - In the nominal scenario, SCC only affects the WP closure lid welds. The WP shell (including the non-closure lid) is heat treated to relieve manufacturing stresses prior to loading of the spent nuclear fuel. Once filled with the wasteform and sealed, the WP cannot be stress relieved through heat treatment, although the surface of the outer closure lid weld is stress relieved by laser peening or low-plasticity burnishing.

The IRT concludes that relevant failure mechanisms are addressed in the IMARC description of the WP failure model and that the models are appropriate. Furthermore, the IRT concurs with neglecting the effect of thermal ageing on the rate of GC in Alloy 22. Such enhancement was only observed in aggressive boiling 50% H_2SO_4 + 42 g/L $Fe_2(SO_4)_3$. However, tests in more relevant environmental conditions indicated no enhancement (BSC, 2003; 2004a). Therefore, neglecting this factor makes sense.

The IRT suggests that EPRI carry out a Sensitivity Analysis to assess the risk importance of the stifling model. If this is important, the IRT recommends that EPRI provides further evidence to support the stifling model for the expected repository conditions.

ES5.4.2 Failures Caused by Initial Defects

There is a very low probability that some Engineered Barriers (EBS) components placed in the repository would have significant initial defects. These defects would be either detectable faults missed by the inspection procedure, or undetectable, small faults located so as to lead to premature container failure. Failure would occur when the full wall thickness of the EBS component (e.g., DS, WP, WP lid welds) was penetrated. Subsequently, irrespective of the size of the penetration, the EBS component is assumed to offer no further protection. A variety of defects, depending on their type (crack, void, inclusion, etc.), position (weld, sidewall), and size, can be expected.

Some of these defects would lead to rapid failure, whereas others would require some time to grow before perforation occurred.

The IRT concurs that the consideration of initial defects in the containment model makes sense. Furthermore, the assumption of complete failure regardless of defect size is clearly conservative. Regarding documentation of the model in the IMARC 9 report, the IRT had difficulty understanding what specific probability was used for initial defects and what it was based on.

ES5.4.3 Rock Mechanics

IMARC 9 considers rock fall resulting from drift degradation and thermal stresses as part of the nominal scenario. The possibilities for such rock fall were assessed by EPRI, using both EPRI and U.S. DOE analyses. EPRI concluded that U.S. DOE’s Drift Degradation model is appropriate for analyzing drift degradation due to thermal loading and seismic events. Furthermore, supplementary EPRI numerical analyses were conducted using UDEC, a two-dimensional code produced by Itasca.

Overall, the IMARC approach follows the U.S. DOE development. The IRT concurs that the U.S. DOE approach and the subsequent EPRI analyses seem to be state-of-the-art.

ES5.5 Radionuclide Release from the Engineered Barriers System

The source-term model in IMARC 9 calculates the release rates of selected radionuclides from spent fuel upon containment failure and contact with water. The list of radionuclides is developed by screening. Other components of the source-term model include:

- instant and congruent release models;
- wasteform degradation model;
- element-dependent solubility limits.

The release of radionuclides from the EBS and into the Unsaturated Zone (UZ) is also affected by mass transport through the EBS and the EBS-UZ interface. These various aspects are commented on below.

ES5.5.1 Screening

IMARC 9 tracks selected radionuclides based on a screening assessment. The radionuclides assessed in IMARC 9 include: Tc-99, I-129, Th-229, U-233, U-234, U-235, U-236, Np-237, U-238, Pu-239 and Pu-240. Potentially important radionuclides in other assessments of spent nuclear fuel disposal include Cl-36, Se-79, and Ra-226 and its progeny. The IRT recommends that EPRI documents the radionuclide screening assessment within the IMARC 9 documentation.

ES5.5.2 Instant Release

The instant release model in IMARC 9 represents both gap inventory and grain-boundary release through the use of an instant release fraction (IRF). This is a conservative and adequate model for the assessment purposes. However, there is no discussion of the derivation of the IRF in the IMARC 9 document. The IRT recommends that EPRI includes a section on the selection of IRF parameter values, their justification and the mathematical implementation of instant release in the model.

ES5.5.3 Wasteform Degradation

Spent fuel is assumed to undergo rapid alteration in the Yucca Mountain repository following waste package and cladding failure because of assumed oxidizing conditions. Radionuclides bound within the spent-fuel matrix are assumed to dissolve into water congruently with spent fuel alteration. A constant spent-fuel alternation rate is assumed. The IRT believes that this alteration time is very conservative for the following reasons:

The dissolution rates were determined from once-through flow tests. As uranium concentrations in the surrounding solution increase, there will be a smaller diffusive gradient driving dissolution.

No credit was taken for the precipitation of alteration products, especially in the presence of Ca and Si. Although the absolute protective nature of such a precipitates is uncertain, they would be expected to at least partially block the underlying UO_2 surface and thus reduce the rate of dissolution.

The IRT recommends that EPRI continues current efforts to evaluate the applicability of more mechanistic spent fuel alteration models.

ES5.5.4 Element-Dependent Solubilities

IMARC 9 assumes that the concentrations of dissolved radionuclides cannot exceed their element-dependent solubilities. The IRT focussed the review of element-dependent solubilities on Np-237, because of its potential contribution to the RMEI dose (due to its long half-life, potential mobility in oxidizing conditions and its radiotoxicity).

The IMARC 9 model assumes that Np co-precipitates with secondary uranyl minerals in which Np (V) substitutes for U (VI), with charge balance maintained by substitution of divalent alkaline earth cations by H^+ or monovalent alkali metal cations.

The IRT concurs that this assumption is consistent with empirical data, although such a precipitate has not been directly identified in dripping experiments under Yucca Mountain repository conditions. The EPRI assumption of an Np co-precipitate with secondary uranyl minerals is also consistent with Burns and Klingensmith (2006). Furthermore, the IRT believes that the consideration of schoepite as an end-member of the assumed solid solution, rather than more stable U minerals such as uranophane, is conservative.

The IRT notes that there is some uncertainty surrounding the precise nature of the solid precipitate and because of this the IRT recommends that EPRI carries out a sensitivity analysis to explore the effect of uncertainty in the value of Np solubility on the overall dose results.

ES5.5.5 Mass Transport through the Engineered Barriers and UZ Interface

In IMARC 9, mass transport through the EBS is modelled using the COMPASS code. The IMARC 9 document only describes the COMPASS and COMPASS-UZ interface in general terms. A detailed description of this interface is provided by Wei (2007).

The radionuclide release rate from COMPASS is given by the sum of the advective and diffusive fluxes calculated assuming a zero outer concentration boundary condition. In order to provide input to the unsaturated zone code, which has been implemented with a concentration boundary condition at the upper edge of the unsaturated zone solution domain, the output from COMPASS is translated into a concentration boundary condition using the average advective flow into the unsaturated zone. As pointed out by the IMARC team, this approach of prescribing the input mass flux to UZ may underestimate concentrations at the interface between the near field and the unsaturated zone, but since it ensures consistency in the total mass flux between COMPASS and UZ, it is appropriate.

It appears to the IRT that dripping conditions in the near-field should be correlated to fracture flowing conditions in UZ, but this correlation could not be fully implemented using a single UZ column (see below). It might have been more realistic to use two different columns of the UZ model, where dripping sections discharge to a UZ column with high rate seepage and the non-dripping parts discharge to a diffusion dominated UZ column. However, since currently used UZ boundary conditions imply that migration though the UZ is dominated by seepage, using a single vertical column is justified.

The IRT encourages the detailed documentation of COMPASS, recently undertaken by EPRI and recommends that it is included in the IMARC 9 document. It is also recommended that EPRI should provide an Assessment Model Flowchart (AMF) that gives an overview of IMARC 9 and its various sub-models.

ES5.6 Unsaturated Zone Flow and Transport- UZ – SZ Interface

The IMARC 9 model of the unsaturated zone (UZ) could be used to represent several one-dimensional vertical columns allowing approximation of the spatial variations of repository releases from the repository horizon. However, in its current implementation only one column is used. It is reasonably assumed that the flow and the transport of the radionuclides are directed downwards only. The one-dimensional columns are represented either as a single-porosity, single-permeability or double porosity/double permeability medium thus describing the coupled matrix/fractures interactions.

The IMARC model of the unsaturated flow allows exploration of the sensitivity of the system to the different hydraulic and migration processes that may be active in the unsaturated zone. The simplification to one-dimensional transport appears justified – and its justification has also been explored by sensitivity analyses.

The IRT is concerned about the use of a single vertical column, since this, in principle, would not represent the spatial variability of the rock properties. However, the IRT accepts the argument provided by the IMARC team that in IMARC 9, migration though the UZ is dominated by seepage so that the spatial variability is relatively unimportant. Therefore, using a single vertical column is justified. However, the IRT recommends that the IMARC document explicitly discusses this, and also generally remarks that the selection of a single vertical column is justified for current properties and boundary conditions.

ES5.7 Saturated Zone Flow and Transport

The IMARC conceptual model for flow and transport in the saturated zone is one of fracture flow, but allowing for matrix diffusion (and sorption) into the rock between the flowing fractures. EPRI has assessed the U.S. DOE approach of channelized flow or flowing intervals, but assumed, in contrast to U.S. DOE, that within the flowing interval, the fracture spacings and resulting block sizes will be much smaller than flowing-interval spacing. The SZ (Saturated Zone) code is a general double porosity groundwater flow and transport code composed of two sub-blocks: one block for the water velocity field computation and one block for the radionuclides transport computation. Originally, the model was implemented as three-dimensional, but based on sensitivity studies the present model uses a 2-dimensional representation, set up as two segments: A fractured tuff segment extending from beneath the repository to 15 km down gradient, and an alluvial segment extending from 15 km down gradient to the location of the Reasonably Maximally Exposed Individual (RMEI) 18 km down gradient, the “compliance point.” as established by the U.S. EPA. The flow boundary conditions are the spatially variable water inflow rate at the upstream boundary of the SZ computational domain, a temporally variable water infiltration rate at the bottom of the UZ column(s) under the repository, and as a constant infiltration rate over the rest of the water table. The values used are derived from U.S. DOE analyses. The output from the saturated zone is calculated as the total discharge in the plume divided by the representative volume to produce concentrations.

The overall conceptual model appears consistent with the U.S. DOE assessment of the saturated zone, but the resulting retention offered by the saturated zone depends critically on the boundary conditions (infiltration at the top surface and inflow rate at the upstream boundary), the used block size, and flow “focusing” caused by the flowing intervals and the matrix diffusivity and sorption. The IRT agrees that it is correct to only consider the flow over the flowing intervals, and increase the flux in the SZ by dividing the average flux by the percentage of the vertical profile representing flowing intervals. The IRT also agrees that block sizes determined by the distances between flowing intervals, rather than the distance between the flowing fractures within the flowing intervals is unnecessarily conservative. However, the IRT notes that basing the block size on the fracture spacing is strictly only valid in case the flow is equal in all fractures and flowing intervals. In case of uneven flow between fractures, the effective block size is a function of the distance between the fractures carrying most of the flow. Furthermore, while the applied boundary conditions for flow and transport are generally justified, it should be noted that flow, and thus retention, in the saturated zone will depend critically on the inflow rate at the upstream boundary of the SZ computational domain and the constant infiltration rate over the rest of the water table. These aspects should be better acknowledged in the IMARC documentation and the input values used, when deviating from U.S. DOE values, need better justification.

The SZ code appears fit-for-purpose, and the sensitivity tests carried out fully support the reduction to two-dimensions – and possibly even to a one-dimensional solution – , given the fact the current biosphere endpoint makes transverse dispersion a non-issue. The approach for calculating concentration at the compliance point appears justified.

ES5.8 Biosphere

EPRI’s biosphere model is a compartmental model which includes the following exposure pathways:

- Drinking of domestic water;
- Bathing in domestic water;
- Inhalation of soil and other dust suspended in air;
- Inhalation of irrigation water;
- Ingestion of soil;
- External exposure to soil;

- Ingestion of food products, including crops (root and green vegetable, grain and fruit) and animal products (beef, chicken and eggs).

This compartment model is used separately from IMARC to calculate a set of Biosphere Dose Conversion Factors (BCDFs), which are used as inputs to the IMARC TSPA calculations. EPRI's overall approach to developing and justifying its compartment model of the biosphere is appropriate and consistent with international practice. The approach is also similar to that of the U.S. DOE.

The IRT has suggestions for improvement of the biosphere model regarding the following aspects:

ES5.8.1 Biosphere Climate Change

The IRT notes that some features of the biosphere are likely to be climate dependent (e.g., irrigation rates). However, the model assumptions are consistent with the regulatory context for the assessment.

ES5.8.2 Exposure Pathways

The IRT notes that the U.S. DOE (2007) biosphere model includes a pathway that is not considered in the EPRI model, namely consumption of fish, farmed in radionuclide-contaminated water. The basis for the inclusion of this pathway in the US DOE biosphere model is that fish-farming is currently practiced in the Amargosa Valley. The IRT recommends that EPRI considers the potential significance of such a pathway.

ES5.8.3 Biosphere Transfer Model

IMARC 9 uses a K_d for modelling radionuclide retardation in soil. This is commonly the approach used in safety assessments. It should be noted that for some radionuclides, such as Tc-99, this is a conservative approach because processes, such as chemical reduction and co-precipitation (e.g., Abdelouas *et al.* 2005; Zachara *et al.* 2007) may tend to further retard migration. The IRT notes that it would be useful to add a discussion on these processes in the report.

ES5.8.4 Data and Parameter Values

The IRT has found that the traceability of the data used in EPRI's biosphere modelling is very good. Nevertheless, it would be useful to improve the IMARC 9 documentation and explain the reasons for changes to the BDCFs that have occurred in IMARC 9 BDCFs as compared to IMARC 6 and 7. With regard to data selection and the use of up to date data, it is noted that EPRI (2007) cites Ashton and Sumerling (1988) as the source of dose coefficients for external irradiation from soil, whereas more recent data may be available (e.g., U.S. EPA, 2002). The IRT recommends therefore, that at an appropriate stage in its safety assessment process, EPRI reviews and updates its documentation and biosphere data.

ES5.8.5 Parameter Uncertainty

EPRI's biosphere modeling involves a large number of parameters, many of which are uncertain. For example, animal product transfer factors and retardation coefficients may well vary over several orders of magnitude. IMARC 9, however, uses single BDCFs for each radionuclide. The IRT suggests that EPRI considers undertaking further analysis of the significance of uncertainties in the values of biosphere input parameters, and clarifies which BDCFs it is taking forward into TSPA (i.e., best estimates, distributions, means, medians or other type of central value), and explains why the values used in TSPA are consistent with its assessment context.

ES6 Integrated Model and Interpretation of the Results

IMARC 9 provides an integrated presentation of the total repository system and captures the main processes and their interactions. In addition to comments on specific sub-models (above), the IRT reviewed overarching issues related to the integrated model and interpretation of the modelling results. Comments on these issues are provided in the following paragraphs.

ES6.1 Conservatism and Realism

The IRT concurs that IMARC 9 is "fit for purpose" in the sense that it provides a risk-based methodology for integrating information from various disciplines affecting long-term repository performance and focuses on a reasonable expectation of the dose consequence to the RMEI as defined by U.S. NRC. IMARC 9 is a very well integrated model which focuses on those processes which could affect the long-term performance of the repository.

The U.S. NRC 40 CFR 197 and 10 CFR 63 call for the performance of analyses that are consistent with a "reasonable expectation" philosophy as opposed, for example, to a "most conservative" philosophy. The IMARC 9 code is generally consistent with the "reasonable expectation" philosophy and the applicable regulations, although some conservatisms in the IMARC models remain (e.g., the spent fuel dissolution rate, neglecting defect size in the modelling of instant containment failure).

The IRT strongly supports work carried out by the EPRI team on the deliquescent brines scenario. This is an important study showing that such brines are unlikely to form, would not be stable if formed, and would not lead to LC, even if they formed and were stable (EPRI 2004b; Apted et al. 2006). The IRT agrees therefore that eliminating deliquescent brine formation and consequent early failure of WPs by LC is justified.

The IRT recommends that EPRI continues to study ways to move away from conservative assumptions (which are essential in the absence of sufficient data and full mechanistic understanding) towards more scientifically credible and realistic assumptions. This is important, particularly for risk-sensitive processes. For example, if a sensitivity analysis shows that the spent fuel dissolution rate in IMARC 9 is risk sensitive over the time-frame of interest, it would be useful to study the availability of data and the feasibility of developing a less conservative, and a more mechanistic fuel alteration model. The IRT supports an initiative being undertaken in this regard, by EPRI.

ES6.2 Treatment of Uncertainty

Uncertainty in input parameters is propagated using two different methods. The primary method of uncertainty propagation in IMARC 9 is based on a logic tree approach. In this approach, parameters are specified as high, moderate, and low values with probabilities associated with each. The second method of uncertainty propagation is based on Monte Carlo (MC) methods. MC analysis has been used in the areas of EBS degradation and BDCF calculation to generate distributions, means or median values for use in the TSPA.

The event tree approach is an approximation to a full MC with continuous pdf's. EPRI should consider carrying out sensitivity analyses to assess whether the approximation introduced by using discrete pdfs significantly affects calculated dose to the RMEI. Furthermore, it is recommended that EPRI justifies the selection of the various pdfs in IMARC. The focus of this documentation effort should be risk-informed.

ES6.3 Sensitivity Analysis

The IMARC 9 draft document focuses on description of assessment methodology and its justification, and less on results and their interpretation. Some sensitivity analyses are presented as part of the rationale for the development of some of the component models, but the dose consequences of the nominal evolution scenario are only shown in the IMARC 9 document for a best-estimate case.

The IRT recommends that the results of the IMARC 9 probabilistic assessment be subject to a systematic sensitivity analysis to identify which parameter uncertainties contribute most to the uncertainty in the calculated total dose rates.

In addition, IMARC 9 includes model uncertainties. Some of these uncertainties are not captured in the IMARC 9 probabilistic calculations (they are represented by parameter values which are means or medians derived outside of IMARC). The IRT recommends that model uncertainties be addressed in a systematic sensitivity analysis. This sensitivity analysis could be based on risk insight from existing assessments and detailed modelling work which could guide priorities towards risk-sensitive areas.

ES6.4 Code Inter-Comparison

According to the IMARC 9 report, ongoing verification activities ensure that the code and its constituent parts are correctly implemented. The code is maintained under a configuration management system. Thorough testing is conducted of all changes to the code that are implemented, and this includes benchmarking against analytical solutions and alternative computer codes, as appropriate.

The IRT concurs with EPRI's statement on the importance of code-intercomparison activities for the various "sub models" that make up IMARC 9. Such comparisons are useful for understanding assumptions and modelling approaches, as well as the effects of certain parameter values and data. Benchmarking is also important for understanding differences between different modelling approaches, and whether these differences are methodological or related to particular sets of parameter values. Once the differences are understood and resolved, the similarity between results using different models can be used to enhance the scientific credibility of the models. The IRT recommends that significant benchmarking activities should be documented.

ES6.5 System Understanding

Many of the U.S. DOE models are incorporated in IMARC 9 via either lookup tables or failure distribution curves. When IMARC 9 deviates from the U.S. DOE conceptual model – this is generally justified based on an independent assessment of the issue and with focus on processes which are important for system performance. The IMARC team has also developed system understanding by its previous sensitivity analyses. Overall IMARC 9 appears to provide very good insight into risk-important processes of the explored repository system.

The IRT understands that the system understanding and model selection are based on critical reviews of the U.S. DOE work by the EPRI team. Such reviews are documented in several of the IMARC reports. However, the IRT recommends that EPRI improves the overall documentation on the final judgements made based on these critical reviews. This would enhance traceability and credibility of the model.

ES6.6 Information Quality and Management

The IMARC 9 document does not include a description of EPRI's approaches to assessing input data quality or data management. In the IMARC 9 report the adequacy of data is generally justified by reference to U.S. DOE work and documents, but there is no pre-defined procedure for justifying and accepting EPRI's input data. The IRT has found no specific examples of non-justified data being used, but the IRT recommends that EPRI should consider making the use of suitable information quality procedures an integral part of conducting assessments with the IMARC code.

EPRI is currently developing and implementing a configuration management system to demonstrate even better control of its code development activities - the IRT encourages EPRI to describe this work in the IMARC report.

The IRT notes that the justification for omitting particular processes or features from certain IMARC sub-models is sometimes based on the expected or actual output of other sub-models. While such an approach is acceptable, the justifications for the sub-models may be interdependent and there might be a risk that these interdependencies could be forgotten by individual team members when further developing a sub-model or if there is an important change in input data. To mitigate this potential problem the IRT recommends that EPRI should maintain a central record of the modelling assumptions made.

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INTRODUCTION

1.1 Background

A total system performance assessment (TSPA) will be a key feature of the anticipated U.S. Department of Energy (U.S. DOE) license application for the candidate Spent Nuclear Fuel (SNF) and High Level Waste (HLW) repository at Yucca Mountain. Recent TSPAs, in keeping with current regulations, model the evolving performance of the repository system over one million years, estimating the potential releases of radionuclides from the repository into the accessible environment as the engineered features of the repository slowly degrade over time. The Electric Power Research Institute (EPRI) has conducted independent TSPAs of the Yucca Mountain repository to gain its own insight on important repository system features, events and processes (FEPs) with respect to estimates of radiation dose to a hypothetical "reasonably maximally exposed individual" (RMEI) living downstream of the Yucca Mountain repository, as defined by US EPA (40 CFR 197). IMARC EPRI's TSPA code was not designed by EPRI to provide an independent comprehensive TSPA but rather to provide an assessment of:

- what processes are likely to happen; and
- impact of these processes on the radiation dose estimate to the RMEI

The focus of the EPRI TSPAs is on the disposal of spent commercial fuel.

This report presents the results of a peer review of EPRI's methodology for TSPA, keeping in mind the EPRI TSPA objectives. The EPRI TSPA methodology is represented by the IMARC code. The IMARC code has been developed by EPRI over the past 18 years in an attempt to reflect corresponding developments in the engineering design, the site-characterization database and the overall scientific data underpinning the TSPA. The IMARC Version 9 (EPRI, 2007) is the focus of the peer review presented in this report.

Features, events and processes addressed in IMARC Version 9 (referred to as IMARC 9 in this report) include climate change, net infiltration, unsaturated zone groundwater flow focusing on groundwater seepage into the repository drifts, containment by drip shield, waste package, and cladding, the source term (radionuclide release from these Engineered Barriers), radionuclide transport through the unsaturated zone and saturated zone, and multiple exposure pathways in the biosphere. IMARC 9 treats uncertainty model parameters by a logic tree (discrete uncertainty values) formalism. Although the code was developed to address the "nominal release" scenario (which does not include unlikely events), more recent modifications of IMARC have been made to evaluate "natural event scenarios" such as an igneous event or an earthquake event.

1.2 Terms of Reference

The peer review presented in this report has been conducted by an international team of experts (see Appendix A) according to the Statement of Work (see Appendix B) agreed upon between EPRI, Monitor Scientific and the International Review Team (IRT). Monitor Scientific has managed the development of IMARC 9 on behalf of EPRI.

1.3 Objectives

The primary objective of the IRT is to review and critically analyze the TSPA methodology and rationale used in the development of IMARC 9 including its sub-models, in view of current scientific knowledge and understanding. Additional IRT objectives are:

- to comment on the adequacy of the IMARC 9 methodology for supporting the *EPRI's* objective of developing an independent code for gaining risk-informed insight into major features, events and processes associated with the YM TSPA;
- to provide recommendations for specific improvements that would help IMARC's continued role in evaluating issues and sensitivities associated with the YM TSPA.

1.4 Scope

This review is the outcome of the work of an international team of three members, over a period of about three months. The main focus of the review has been a draft of the IMARC 9 model documentation (EPRI 2007), with a partial review of key supporting documents. Given the time constraints, the IRT was primarily concerned with high level features of the model rather than with details. Only the normal evolution scenario was included in the scope of work. Volcanism was beyond the scope of work. Seismic activity was included because some level of limited seismic events is part of the normal evolution scenario. Volcanism and human intrusion scenarios, however, were not part of the scope of work of the IRT.

It is expected that IMARC will continue to evolve to address recent developments in the Yucca Mountain disposal concept, such as new waste package designs for Transportation – Aging – Disposal (TAD) and for the co-disposal of defence HLW and naval fuel. These, recent developments are beyond the scope of this review.

Each section (of EPRI 2007) was reviewed by at least two members of the IRT.

The International Atomic Energy Agency's (IAEA's) Improvements on Safety Assessment Methodologies (ISAM) model (Figure 1-1) was used as a framework for the peer review to ensure a complete and systematic review of the IMARC 9 draft report by the IRT.

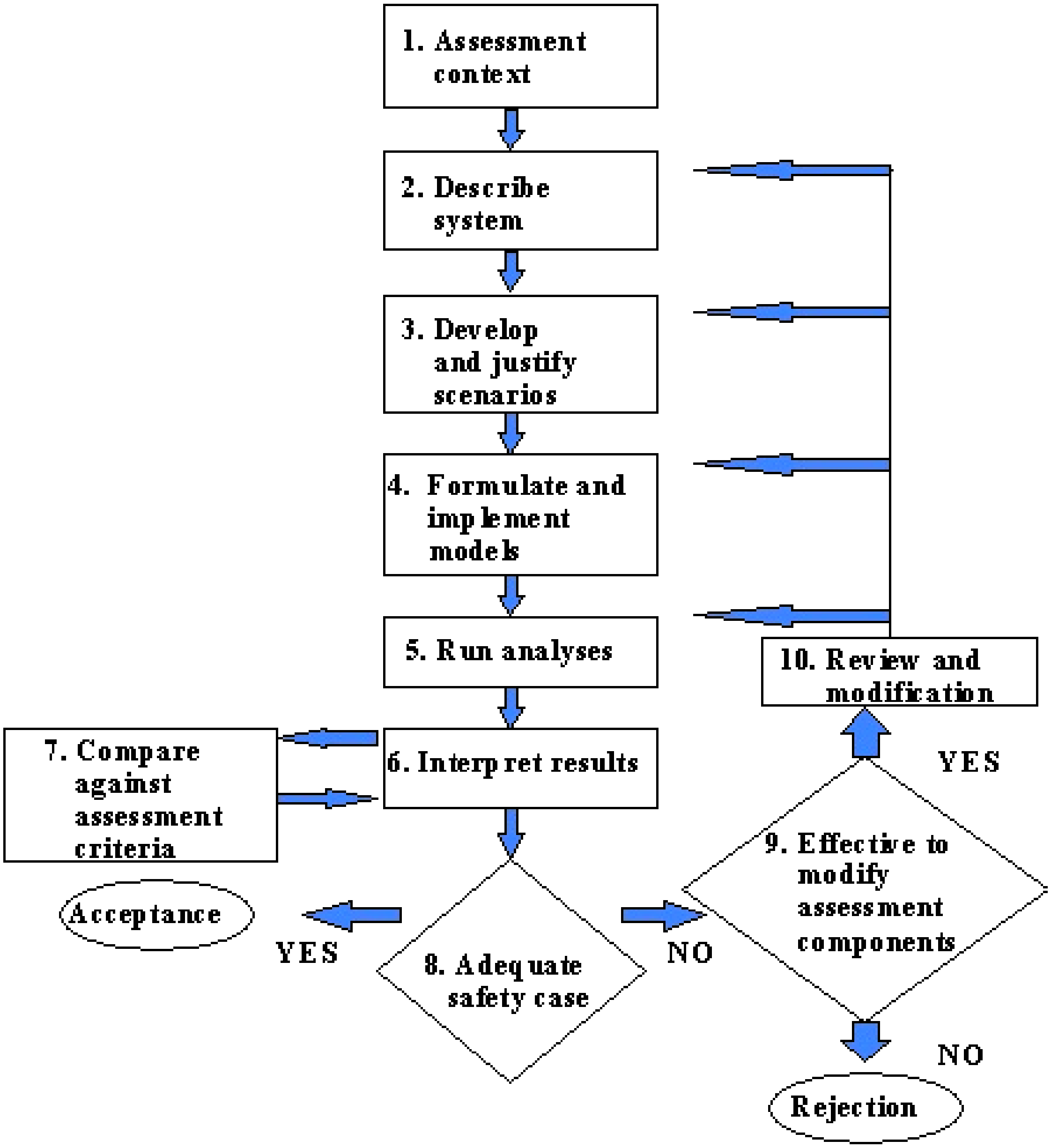

Figure 1-1
The Internationally Accepted IAEA "ISAM" Methodology (IAEA, 2004)

The brief labels in the boxes in Figure 1-1 are given expanded perspectives below by identifying relevant questions specific to the context of the IRT review responsibilities:

1. Assessment context: Have the U.S. legal, US regulatory, and stakeholder (i.e., EPRI) roles and perspectives relevant to performance assessment of the Yucca Mountain repository in general, and to the IMARC code development in particular, been presented and adequately referenced? Is there a clear presentation of the IMARC 9 assessment context? Is this consistent with the "reasonable expectation" assessment guidance proscribed in the U.S. Environmental Protection Agency's Yucca Mountain safety standard?

2. Describe system: Has sufficient description been provided of the natural and engineered barriers of the Yucca Mountain repository? Have the relevant processes affecting long-term containment and possible radionuclide release and transport to the accessible environment been adequately identified and described using traceable references?
3. Develop and justify scenarios: Has the EPRI approach of using technical experts to conceptualize and abstract process sub-models to be included in (or excluded from) the normal evolution scenario been adequately described? Has this approach been applied in a manner consistent with EPRI's assessment context? Are references provided to reports where the IMARC 9 code has been extended to analyze 'natural event' scenarios (e.g., igneous and seismic events)?
4. Formulate and implement models: Do the mathematical sub-models implemented in IMARC 9 adequately capture and represent the abstracted conceptual processes? Are verifications of the models presented and are these verifications adequate within the context of EPRI assessment philosophy? Are any limits to the applicability of the sub-models identified? Are credible data sources identified, and has the basis for selection of ranges of input data been presented? Are linkages between process sub-models described and are these linkages reasonable within the assessment context?
5. Run analyses: Are representative IMARC 9 analyses presented? Are the analyses clearly documented and traceable to published references?
6. Interpret results: Within EPRI's assessment context, are reasonable and technically defensible interpretations of sub-system and total system performance of a Yucca Mountain repository presented?
7. Compare against assessment criteria: Could IMARC 9 results be compared properly with the draft US regulatory criteria and safety standard for Yucca Mountain? What limitations, if any, are there to the comparisons?

Box 8 in Figure 1-1 relates to a decision regarding formal acceptance of a safety analyses or safety case to support a license application. The IRT review has not considered this step in the review of the IMARC Version 9 report.

Boxes 9 and 10 in Figure 1-1 relate to possible modifications of the assessment, including the assessment model/code. The IMARC 9 draft report does discuss modifications made to the IMARC code leading to the present Version 9, in part to show how historical factors (e.g., changing repository design, changing regulations, previous safety assessment results) have led to the current structure and capabilities of IMARC Version 9. While the IRT review focuses primarily on the IMARC 9 code, the IRT also comments on whether appropriate modifications have been made to the IMARC code in response to previous analyses and the evolving situation of the U.S. nuclear waste disposal program. The appropriateness of such modifications is evaluated, however, with respect to EPRI's assessment context and EPRI's role within the U.S. nuclear waste disposal program, i.e. the main question considered by the IRT is: is IMARC 9 fit for purpose?

1.5 Report Outline

Section 2.0 addresses general aspects of the IMARC 9 review. If comments on the adequacy of IMARC 9 regarding Boxes 1 to 5 and 7 in the ISAM methodology. It also provides general comments on the documentation (Part of Box 4 of ISAM).

Section 3.0 comments in detail on the formulation and implementation of the sub-models (ISAM Box 4).

Section 4.0 addresses overarching issues, such as: conservatism, the treatment of uncertainty, sensitivity analysis, benchmarking, information quality and management, and interpretation of results (ISAM Box 6).

Section 5.0 summarises conclusions and recommendations.

2

GENERAL ASPECTS

This section examines how at a general level IMARC 9 addresses steps 1 to 5 of the ISAM safety assessment methodology.

2.1 Assessment Context

IMARC Description

The assessment context comprises the basic framework for conducting safety assessment (IAEA 2004a, b). Paraphrasing IAEA (2004a, b), the assessment context comprises key information regarding the purpose of the assessment, the regulatory framework, the assessment philosophy adopted, the end-points of the assessment, disposal system characteristics, and the assessment timeframes. Put simply, the assessment context determines or describes what is being assessed, why the assessment is being conducted, and how the assessment is being approached.

EPRI has conducted independent TSPAs since 1989. During that time, the purpose of EPRI's assessments has varied but only slightly, and this has been due largely to shifts in the status of the Yucca Mountain Programme. For example, the stated purpose(s) of EPRI's assessments have included:

- To encourage U.S. DOE to complete integrated assessments characterizing Yucca Mountain as a prospective site for an HLW repository (EPRI 1996a).
- To provide technical insight to the utilities and others on factors significantly contributing to disposal system performance (EPRI 1998).
- To help U.S. DOE prioritize and manage technical issues (EPRI 1998).
- To gain its own insight on important repository system Features, Events and Processes (FEPs) with respect to estimates of radiation dose to a hypothetical Reasonably Maximally Exposed Individual (RMEI) living downstream of the Yucca Mountain repository (EPRI 2007).
- To provide an independent perspective on the many technical and scientific issues that may arise during the course of the regulatory review process (EPRI 2007).

The most recently published full description of EPRI's assessment context is provided in (EPRI 2002a) and is summarised in Table 2-1.

Table 2-1
Summary of the Assessment Context (after EPRI 2002a)

Component	Description
Assessment Purpose	Demonstrate compliance with regulatory requirements Contribute to confidence of policy makers, the scientific community and the public Guide later stages of repository development Guide research priorities
Assessment End-Points	Annual individual effective dose
Assessment Philosophy	'Equitable' (similar to 'realistic' or 'best estimate'), except with respect to the critical group definition, for which a 'cautious' (similar to 'conservative') approach is adopted
Repository Type	Yucca Mountain HLW repository
Site Context	Amargosa valley Sub-tropical arid (desert climate)
Geosphere/Biosphere Interface	Well intruding into an aquifer plume with abstraction at a rate consistent with domestic and agricultural use
Source Term	Constant unit concentration in abstracted water maintained indefinitely for each set of relevant radionuclides
Societal Assumptions	Agricultural community, adopting modern practices (machinery and methods) for cultivation and animal husbandry
Time Frame	Up to 1 million years. Release via well continues continuously for long enough for concentrations to reach steady state in the assumed biosphere.

IRT Assessment

Based on the documented record of the development of the IMARC model and recent meetings with EPRI and its assessment team, the IRT is content that EPRI has continued to update its assessment context appropriately in response to changes in the Yucca Mountain Programme and the development of regulations etc, throughout the model development period, including since 2002.

For example, EPRI has taken account of recent regulatory guidance on the use of the RMEI approach, on the abstraction of contaminated groundwater (the Geosphere/Biosphere interface), and on the assessment time frame. EPRI is also aware of at least some of the possible implications of potential further developments in regulations (e.g., the possible adoption of the median rather than the mean dose as a compliance measure).

The consequences of both EPRI's role in relation to the licensing of a repository at Yucca Mountain and its assessment context need to be understood, because they affect both EPRI's approach to safety assessment, and any assessment of the adequacy of EPRI's safety assessment work, for example, this review.

To fulfil their purpose(s) EPRI's safety assessments have to be scientifically credible and of sufficient quality to allow a balanced examination of the different FEPs that may affect the performance of a repository at the Yucca Mountain site. This requires that the safety assessments should, to the extent possible, be based on realistic assumptions and data (in order that the relative importance of the different FEPs can be discriminated), but does not necessarily require EPRI either to investigate all conceivable (e.g., low probability and for minor consequence) FEPs, or to make a comprehensive examination of all quantifiable uncertainties.

For example, it may be sufficient for EPRI's purposes to identify a particular FEP and show that it could potentially be important using a relatively simple but not unrealistic model, without going in to great detail or completing comprehensive sensitivity analyses; in such a case U.S. DOE might wish to conduct more detailed or extensive investigations. Conversely, it may be possible for EPRI to use such a simple model to show rapidly and efficiently that a certain FEP is insignificant in comparison to other FEPs that are known to be important to disposal system performance.

Based on its review work, the IRT considers that EPRI has assembled an impressive multidisciplinary team of scientifically credible experts to lead the various parts of its assessments and model development work. This team has successfully addressed the EPRI TSPA objectives.

EPRI notes that 40 CFR 197 and 10 CFR 63 call for the performance of analyses that are consistent with a "reasonable expectation" philosophy as opposed to a "most conservative" philosophy. The IRT considers that EPRI has adopted an appropriate assessment context according to its role and that EPRI's implementation of the IMARC code is consistent with the "reasonable expectation" philosophy and the applicable regulations. Comments on some conservatism in the IMARC models are given in Section 3.

However, EPRI opines that EPRI's documentation of its assessment context needs to be updated to reflect the current situation and could also explain more fully why it takes its selected assessment approach. More detailed review comments on aspects relating to the assessment context are provided in Section 3, particularly in Section 3.8.

2.2 System Description

IMARC Description

EPRI does not conduct its own site investigation work and so relies instead on site characterisation data collected by or on behalf of the U.S. DOE. Similarly, EPRI assesses the potential performance of the U.S. DOE's proposed repository and EBS (Engineered Barrier System) designs, and so relies on design information published by or on behalf of the U.S. DOE[2]. For some other parts of the disposal system, however, such as the climate system and the biosphere, EPRI takes relevant information from a range of published sources including the scientific literature and the US DOE.

IRT Assessment

The IMARC 9 documentation focuses very much on the IMARC model itself and does not set out to provide detailed descriptions of the disposal system and its components, beyond those necessary to understand what the model is seeking to represent. EPRI's reliance on information regarding the disposal system characteristics published by the U.S. DOE and others is appropriate, but the IRT considers that the current IMARC 9 documentation could be improved by providing some more detail on the disposal system and its (geometrical) conceptualization. The IMARC reports should certainly refer to the most recent information from the Yucca Mountain Programme on site characterisation and repository and EBS design issues.

2.3 Development and Justification of Scenarios

IMARC description

EPRI's development of IMARC has tracked the evolution of Yucca Mountain regulations, disposal system design, and conceptual understanding of the proposed repository over the years and current emphasis is on three primary scenario variants (EPRI 2007):

- A nominal scenario, which comprises the FEPs that are expected to occur (as opposed to unlikely FEPs), including certain seismic effects.
- An igneous intrusive scenario.
- An igneous extrusive scenario.

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[2] To the knowledge of the IRT, EPRI has not developed or made formal assessments of its own alternative repository or EBS designs, although some members of the EPRI assessment team have at various stages of the program suggested alternatives that could be considered (e.g., tunnel backfills).

The igneous intrusive scenario has been addressed using IMARC in EPRI (2005). The FEPs associated with the igneous extrusive scenario are very different than those implemented in IMARC, and as a result, this scenario has been evaluated using a different modeling approach (EPRI, 2004a; 2004c).

The inadvertent human intrusion scenario established in 10 CFR Part 63 has not been addressed in IMARC or in other EPRI analyses for two reasons:

- 10 CFR Part 63 prescribes a stylized examination of inadvertent human intrusion manner and does not permit significant alternative viewpoints (EPRI 2007).
- Inadvertent human intrusion scenarios are not expected to be significant in licensing of the Yucca Mountain repository (US DOE/OCRWM, 2000).

IRT Assessment

In general terms, EPRI has followed an approach to the identification and justification of scenarios and models that is largely based on the regulatory context for the assessment of a repository at Yucca Mountain, coupled with expert judgement regarding which FEPs should be included (or excluded) from TSPA models and sub-models (see Section 2.4.1). The IRT considers that this is an appropriate approach, given EPRI's assessment context and its focus on developing a model that provides a reasonable representation of expected system behaviour. The focus of the IRT's review has been on the nominal scenario. It is proposed that a future review will address EPRI's application of IMARC to alternative credible scenarios such as igneous events, rock-fall and expanded capacity of the repository.

IRT notes that consistent with the objectives and priorities, EPRI has not conducted a formal FEPs audit to confirm that all relevant FEPs are appropriately accounted for (or eliminated from) in its chosen scenarios and models. A systematic formal audit of FEPs would be expected of the U.S. DOE as the potential implementer of the repository at Yucca Mountain. Furthermore, it is recommended that EPRI reviews the U.S. DOE FEPs documentation for comparison with its assessment models.

Comments on the representation of the scenarios using IMARC and its various sub-models are provided in Section 3.

2.4 Model Formulation and Implementation

IMARC Description

EPRI's approach to model formulation and implementation has been to contract a team of experts, collectively possessing expertise in a wide variety of relevant disciplines. Individuals from this team have been given responsibility for developing detailed conceptual models and software to represent various parts of the disposal system, according to their areas of expertise. These experts decide, on the basis of expert judgement, whether and how individual FEPs should be included in (or excluded from) the detailed models, and give advice on how the detailed models should be represented in TSPA analyses (e.g., through appropriate simplifications). A lead contracting organisation (Monitor Scientific) maintains and runs the IMARC code, which provides a Total Systems Performance Assessment (TSPA) capability based on the various detailed models or their outputs. The lead contractor also coordinates periodic meetings of the EPRI expert team at which elements of the model are discussed and reviewed.

IRT Assessment

The IRT believes that in broad terms it understands the model formulation process that has been followed, although this is not described in great detail in EPRI (2007). The IRT considers that the model formulation process itself is a reasonable one: it relies on ‘cross-review’ of work by other members of the assessment team and by other peer reviewers (such as in this review), as well as suitable controls over the quality of the work and software development. The IRT suggests that EPRI should consider reviewing and adopting centralised methods (e.g., knowledge management approaches) for recording and controlling changes to model assumptions, data and parameter values, and for making these readily available across the expert team (e.g. the Vignette knowledge management system used by the Belgian Agency for Radioactive Waste). Overall, the model formulation process followed by EPRI results in a very well integrated and “fit for purpose” TSPA model.

2.4.1 The IMARC 9 Conceptual Model

IMARC Description

EPRI (2007) identifies a wide range of FEPs that are considered in the IMARC 9 code and its sub models, viz:

- Details of present and future climates affect the amount of rainfall, and human behaviour (use of surface versus groundwater, agricultural practices, etc.);
- Some of the rainfall impacting the surface of the mountain infiltrates deep into the ground (i.e., the upper level of the unsaturated zone);
- The groundwater infiltrating deep into the upper parts of the unsaturated zone may laterally redistribute due to heterogeneous fracture and matrix properties;
- Some of the groundwater percolates into the drifts within the repository, while the remainder passes around the repository drifts. The relative amounts are a function of the lateral redistribution above the drifts, capillary effects at the drift walls, or, for the igneous intrusion scenario, the hydrologic characteristics of the cooled magma in the drifts;
- Some of the groundwater seeping into the drifts may drip onto the drip shields or, if the drip shields have somehow failed, onto the underlying waste packages;
- The drip shields, when functioning, prevent groundwater from dripping onto the underlying waste packages;
- The drip shields can fail to function due to either improper initial emplacement, seismic and rockfall processes, or corrosion processes such as general corrosion and hydride embrittlement. Details of the drip shield failure can affect the ability of groundwater to penetrate through the “failed” drip shields. In the case of the igneous intrusion scenario, drip

shields can also fail to function as a result of being dislodged during initial magma entry into the drifts;

- Waste packages, when functioning, prevent humid air and groundwater from penetrating into the waste packages and prevent the release of gaseous, dissolved, or colloidal radionuclides into the near field;
- The waste packages can fail to function due to seismic, rockfall, and various corrosion processes. In the case of the igneous intrusion scenario, the initial emplacement of magma around the waste packages can lead to other potential waste package failure mechanisms due to high temperatures. Details of the waste package failure can affect the ability of groundwater to enter the waste packages;
- The cladding surrounding the spent fuel can also prevent water from coming into contact with the ceramic UO_2 wasteform itself. Cladding can fail by a variety of mechanisms, including initial failures at emplacement, creep, localized corrosion, and hydride embrittlement. The extent of the cladding failure can limit the extent of wasteform exposure to water entering the failed cladding;
- Water entering into failed waste packages and cladding may be either in the form of condensate from humid air, or dripping groundwater;
- Seepage entering the waste packages and cladding may transport radionuclides released from the UO_2 wasteform. Processes that control the release rate of radionuclides include: solubility limits, groundwater flow rates, wasteform dissolution rates, and tortuous diffusion pathways;
- The released radionuclides are then transported out of the failed waste packages, into and through the lower area of the drifts, and into the lower unsaturated zone. Processes such as fracture/matrix interaction, and radionuclide sorption largely govern the transport rates; and
- The seepage transporting the radionuclides then traverses the saturated zone (SZ) and the far-field to a point 18 km downstream, the "compliance point," where it is assumed to be taken up by the RMEI in a manner that is prescribed by 40 CFR 197 and 10 CFR 63. A variety of RMEI behaviour assumptions (use of contaminated groundwater for drinking and agriculture, indoor and outdoor activities, etc.), along with relevant health physics processes, can lead to committed radiological doses to the RMEI.

IRT Assessment

The IRT considers that the IMARC 9 code and sub-models are based on a reasonable conceptual model and that at least for the nominal scenario they capture the relevant processes affecting long-term containment and radionuclide release and transport to the accessible environment. Other scenarios were not reviewed in detail by the IRT.

The IRT considers that in the vast majority of instances, the model formulation process has led to the development of models and parameters that represent relevant FEPs in a manner consistent with EPRI's assessment context; comments on individual models and FEPs are provided in Section 3, including discussion of certain model conservatisms.

2.4.2 Model Implementation

IMARC Description

The conceptual model described above is implemented in the IMARC code and its sub-models as follows:

- The IMARC code represents climate, infiltration and seepage using appropriate parameters and assumptions regarding water flows.
- The IMARC code uses input data functions describing the rates of container and drip-shield failure, which are derived from the engineered barrier system corrosion sub-model, implemented in the EBSCOM code.
- The IMARC code incorporates three major numerical sub-models describing near-field radionuclide release and transport (the COMPASS code), unsaturated zone flow and transport (the UZ code), and saturated zone flow and transport (the SZ code).
- The IMARC code uses a set of input parameter values in the form of biosphere dose conversion factors (BDCFs) which are derived using the biosphere sub-model implemented in the AMBER code.

The data and parameter values used in the IMARC TSPA modelling are described in various sections of EPRI (2007) and its appendices.

IRT Assessment

The IRT considers that there is no over-riding conceptual difficulty with the use in a TSPA model of a mixture of approaches (sub-models) for representing different disposal system components or FEPs. In fact, it is common practice for safety assessments to rely on input data and parameter values derived from various different types of activity, including, site characterisation observations, experimental measurements, modelling results, and expert elicitations.

However, the IRT notes that in IMARC the justification for omitting a specific process or feature from one sub-model is sometimes based on understanding of the output from other sub-models. This is, for example, the case motivating that the seepage model does not consider the hot sub-boiling phase (see Section 3.3) or for motivating the use of a single vertical column in the unsaturated code (see Section 3.6). While such an approach is acceptable, there might be a risk that these justifications could be forgotten when further developing a sub-model – or if there is an important change in input data. The IRT considers that this reinforces its suggestion that EPRI should consider managing its safety assessment assumptions centrally (e.g., using a knowledge management system, database or similar) and communicate these effectively across the expert team.

There is also a requirement to ensure that the interfaces between the various sub-models are treated properly in the TSPA code and that these linkages are described in the assessment documentation. In this respect the IRT notes, for example, that the different sub-models used within IMARC employ various different discretisation schemes (e.g., net infiltration values are used as input to the IMARC model with a variable (smaller) time step for internal calculations to provide some control of initial numerical instability following the step changes in net infiltration. A second example is that the COMPASS sub-model is based on transfers between a relatively few model compartments, whereas the UZ (Unsaturated Zone) and SZ (Saturated Zone) codes employ finer grids and finite difference solution approaches). The IMARC 9 documentation should, therefore, describe these different discretisation schemes and explain why in practice, given the various grid and compartment sizes and timesteps actually used in the calculations, unacceptable errors (e.g., in calculated flows and radionuclide transport rates) are not introduced at the interfaces between the sub-models.

The IRT commends the EPRI team for its understanding of the need to critically review and evaluate the data from which parameter values to be used in TSPA are selected or derived. In general the IRT believes that the EPRI assessment team has selected reasonable (i.e., not extreme) parameter values from credible references. However, there are some instances where the IMARC 9 documentation could provide more information on the rationale for parameter value selection and every effort should be made to continue to improve the traceability of referencing so that parameter values can be traced to their origin.

Specific details of the implementation of the sub-models and the data and parameter values used are discussed in Section 3. Verification of the IMARC code and sub-models, and the approach to the treatment of uncertainty using IMARC are discussed in Section 4.

2.5 Analyses Documentation

IMARC Description

IMARC 9 is documented in EPRI (2007) which makes reference to a range of previous EPRI reports on earlier versions of the IMARC model and also refers to a series of other EPRI reports on particular issues and FEPs. At this stage, EPRI (2007) provides only limited example results from IMARC 9. For example, Figure 9.1 of EPRI (2007) is a graph of assessed mean dose versus time for a set of key radionuclides.

IRT Assessment

At the highest level of comment the IRT considers that it would be beneficial to EPRI if the IMARC 9 documentation was structured and written systematically so as to describe and explain the rationale for the current assessment context and IMARC model (i.e., as it is today). The draft IMARC 9 documentation provides a useful history of the development of IMARC, but the approach of referring back to many previous reports and earlier versions of the code, and then discussing incremental changes to earlier assumptions, models and data tends to obscure the presentation of the current model. This is a presentational issue and not a criticism of the IMARC model itself, but the IRT considers that it is an important point, particularly in the context of a forthcoming licensing process. EPRI will want to be able to point in a straightforward way to a single clear document that describes its model and gives the justification for the various models and data used.

The IRT understand that it was not the purpose of the draft IMARC 9 documentation to present full results from a safety assessment. When fully presented, the IRT considers that results from the IMARC 9 model could sensibly and credibly be compared with the current draft regulatory criteria and safety standard for Yucca Mountain. As noted above (Section 2.1) EPRI's assessment context is consistent with the "reasonable expectation" philosophy in the applicable regulations, and results from IMARC 9 should provide a credible indication of the expected performance of a repository at Yucca Mountain as long as the assessment takes proper account of the latest information on the waste inventory and the repository and EBS designs[3]. Nevertheless, additional results and sensitivity analyses could be useful in providing risk-informed insight into the IMARC 9 model and the performance of the repository.

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[3] The IRT understands that EPRI safety assessments have not considered all of the waste types in the inventory for Yucca Mountain.

3

SUB MODELS DEVELOPMENT AND IMPLEMENTATION

3.1 Climate Change

Climate and climate change are likely to be important controls on the amount of water that flows through Yucca Mountain and may, thus, affect repository and disposal system performance. Over extremely long periods of time, major changes in the global climate could occur, for example, leading to a transition to a glacial climate (e.g., NAS 1995).

U.S. EPA (2001) stated that over the next 10,000 years, the biosphere in the Yucca Mountain area probably will remain, in general, similar to present-day conditions due to the rain-shadow effect of the Sierra Nevada Mountains, which lie to the west of Yucca Mountain. Nevertheless, U.S. EPA (2001) also specified that "U.S. DOE must in its performance assessments vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions of the changes in these factors that could affect the Yucca Mountain disposal system". Accordingly 10 CFR § 63.305 (U.S. NRC 2001) states that US DOE must "vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system over the next 10,000 years".

Following recent legal challenges, U.S. EPA and US NRC are proposing amended regulations that, amongst other things, address how climate should be considered after 10,000 years. U.S. EPA (2005) proposes that U.S. DOE assume the effects of climate variation, after 10,000 years, are limited to those resulting from increased water flowing through the repository. U.S. EPA (2005) also proposes that U.S. NRC specify, in regulation, the steady-state (constant-in-time) values that U.S. DOE should use to project the long-term impact of climate variation after 10,000 years.

According to the U.S. NRC (2005), this approach focuses on "average" climate conditions over the long-term, rather than on time-varying aspects of climate (e.g., timing, size, and duration of short-term variations) that can be both uncertain and speculative.

U.S. NRC (2005) considered which parameter or parameters would represent the average climate conditions and identified precipitation and temperature as parameters associated with climate that directly influence the amount of water, or deep percolation, flowing to the repository horizon. U.S. NRC (2005) argues, however, that it is the rate of deep percolation that directly influences repository performance, and U.S. NRC is therefore proposing to specify use of the deep percolation rate to represent the effect of future climate in performance assessments after 10,000 years.

Estimates of deep percolation rate as a fraction of precipitation have been calculated by U.S. NRC (2005) for various climate conditions. 5 to 20 percent of precipitation could reach the repository depth under future hypothetical intermediate/monsoon to “full-glacial” climate conditions. The larger 20% figure reflects “full-glacial” conditions. Given that average deep percolation at Yucca Mountain is approximately 4 percent of precipitation under current conditions, and assuming between 5 to 20 percent as the fraction of precipitation that remains as deep percolation under intermediate/monsoon climates, one may estimate higher average water flow to the repository than is observed today. On this basis, U.S. NRC (2005) proposes use of a time-independent deep percolation rate, after 10,000 years, based on a log-uniformly distributed range of deep percolation rates from 13 to 64 mm/year (0.5 to 2.5 inches/year)[4]. U.S. NRC (2005) notes that these figures result in a mean deep percolation rate of approximately 32 mm/year (1.3 inches/year)[5], a rate that is approximately six times greater than the current rate, representing wetter and cooler conditions (e.g., interglacial and monsoon climate states).

IMARC description

The IMARC code is based on a logic tree approach (EPRI 1990; 2007), which allows selected key parameters (including the net infiltration rate) to be assigned low, moderate and high values, with associated probabilities that describe how likely the parameter in question is to take each of the low, moderate, and high values[6]. The logic tree used in IMARC 9 is shown in Figure 3.1. In conducting TSPA, the IMARC code calculates the dose to the RMEI for each path through the logic tree, and combines these results taking account of the probability of each path.

In conducting TSPA, EPRI assumes that a greenhouse climate exists for the first 1,000 years after repository closure. An interglacial climate is assumed to exist for the next 1,000 years (EPRI, 2007). Following this initial 2,000 year period, a full glacial maximum climate is assumed to persist for the remainder of one million years after present (EPRI 2007). At Yucca Mountain, the glacial climate will be cooler and wetter than at present, but the mean annual temperature is expected to be well above 0°C. The Yucca Mountain area is not expected to have frozen soil conditions or ice cover on any extended basis.

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[4] The low value of the range is derived using the lower estimated fraction of precipitation that results in deep percolation and the lower precipitation rate (i.e., 5 percent of 266 is approximately 13) and the high value of the range from using the higher estimated fraction of precipitation that results in deep percolation and the higher value for precipitation rate (i.e., 20 percent of 321 is approximately 64).

[5] The mean value of a log-uniform distribution of deep percolation that ranges from 13 mm/year to 64 mm/yr is equal to (64 mm/year - 13 mm/year)/[$\log_e$(64 mm/year) - $\log_e$(13 mm/year)] = 32 mm/year.

[6] In some cases, this triangular distribution is replaced by a high-low value set, with only two values of associated probabilities (EPRI 2007).

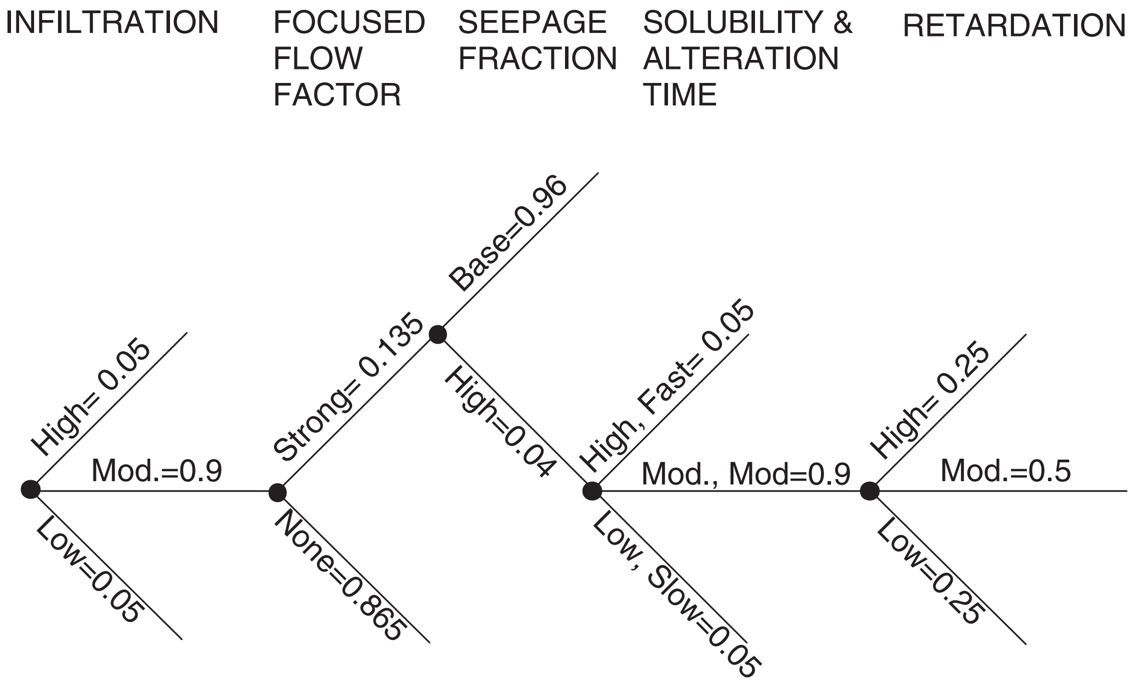

Figure 3-1
Logic Tree of Uncertain Parameters in IMARC 9 (EPRI 2007)

Each climate state is assigned a net infiltration rate, which is considered to be an uncertain parameter in the current IMARC event tree (Figure 3.1). Values for the low, moderate, and high values of infiltration rate currently used in IMARC are shown in Table 3.1. The values for full glacial maximum are based on the U.S. NRC (2005) recommendations, and are about a factor of two higher than EPRI's technical investigations show are appropriate (EPRI 2007). The low infiltration rate is assigned a probability of 0.05, the moderate rate a probability of 0.9, and the high rate a probability of 0.05 (EPRI 2007).

Table 3-1
Net Infiltration Rates used in the IMARC 9 Event Tree Branches (after EPRI 2007)

Period after Closure (years)	**Assumed Climate State**	**Net Infiltration Rate (mm/y)**		
		Low	**Moderate**	**High**
0 to 1,000	Greenhouse	1.1	11	19
1,000 to 2,000	Interglacial	1.1	7.2	9.6
2,000 to 1,000,000	Full Glacial Maximum	13	32	64

IRT Assessment

EPRI's approach to representing climate and climate change in TSPA is generally clear, although the terms 'present-day interglacial', 'greenhouse', and 'full glacial maximum' should be clearly defined, and their use made more consistent in the next revision of the IMARC documentation. Perhaps more importantly, the draft IMARC 9 report (EPRI 2007) does not present the rationale for the assumed durations of the first two climate states, for the infiltration rates used to represent the first 2,000 years after closure, or for the probabilities assigned to each of the low, moderate and high values of the infiltration rate parameter.

The IRT considers that the overall EPRI approach to representing climate change in IMARC 9 is generally consistent with the proposed regulations. An approximation is introduced because IMARC 9 represents the U.S. NRC proposed log-uniform distribution for infiltration rate using a three point discrete distribution (see also Sections 3.2 and 4.2).

The IRT notes that EPRI has reviewed the technical basis for the estimation of infiltration rates at Yucca Mountain and has developed and maintained its own position on the issue, which is that infiltration rates are likely to be generally lower than the values proposed by U.S. NRC (2005). The IRT suggests, therefore, that EPRI may wish to conduct TSPA calculations using different sets of infiltrations rate values (the U.S. NRC values and the EPRI values) to determine the sensitivity of calculated doses to these assumptions (see also Section 3.2). It will of course be important for EPRI to present clearly its technical basis for assumed climate states and infiltration rates, and to justify the inclusion and exclusion of data sources used in coming to its estimates. EPRI may also wish to document, or refer to, studies performed that indicate that the effect of alternative climate scenarios are not significant to TSPA results.

The IRT recommends that EPRI incorporates a discussion of the potential effects of global warming into the IMARC document.

3.2 Infiltration

IMARC Description

Net infiltration is a hydrologic parameter that controls the rate of deep percolation, radionuclide transport, groundwater recharge and groundwater seepage into the repository, and as such, it makes sense to include it explicitly in IMARC. Net infiltration is included in IMARC as a model parameter with assigned values for several climate types (see Table 3.1).

IRT Assessment

Net infiltration is largely dependent on the climatic conditions. It is therefore appropriate that the net infiltration modelling in IMARC is climate dependent. Furthermore, the assignment of low, moderate and high values to the net infiltration event-tree branches is a simple and reasonable approach for capturing uncertainty and variability in this parameter value, commensurate with the available meteorological data.

In addition, this simple approach is justified because in the very long-term, i.e. beyond 10,000 years (when infiltration might actually have an effect on doses and risks from the repository by affecting radionuclide transport from the gradually failing EBS) the infiltration rate in the TSPA has been proposed by U.S. NRC (2005).

In the logic tree approach adopted by IMARC, it is important to ascertain that no significant correlations are missed.

A brief formulation of the infiltration sub model appears in Section 3.2 of the draft IMARC 9 report (EPRI 2007). Specific suggestions for improved documentation of the model formulation include:

- addition of a water balance diagram;
- explanation of the coupling between infiltration, percolation and seepage in IMARC 9;
- clarification of the effect (or lack thereof) of infiltration on Engineered Barriers degradation rates;
- explicit presentation of the model equations that use the infiltration rates (or reference to other sections where these may appear);
- reference to the literature source(s) where the model and model parameters are derived.

Regarding model implementation, as noted above, low, moderate and high net infiltration rates are defined in IMARC 9 for each climate type (Greenhouse; Interglacial; Full Glacial) based on an assessment of project data (EPRI, 1998). As IMARC is periodically updated to reflect scientific progress, the IRT suggests that it would be beneficial to use the IMARC 9 tool to evaluate the dose/risk implications of uncertainties related to selecting the (EPRI, 1998) range of net infiltration rates versus other recent work (e.g., Faybishenko, 2007 or other recent assessments). Since infiltration rates affect percolation through the UZ and groundwater recharge, it would also be useful to carry out a sensitivity analysis to evaluate how sensitive the UZ and SZ radionuclide transport are to uncertainty in the net infiltration rate over the first ten thousand years after disposal. If the only implication of uncertainty in the infiltration rate is uncertainty in the dose due to early container failure and if this uncertainty is high, it would make sense to recommend improved container inspection procedures to reduce the probability of such early failures.

3.3 Seepage

IMARC Description

Seepage, i.e. free water flow, into the disposal drift, is a function of the infiltration, and is affected by the capillary barrier provided by the open tunnel, which at small infiltration rates will allow water to flow around the drift rather than to seep into it. It is important to note that the heterogeneous nature of the fractured tuff implies that the average net infiltration will be focused into some areas and directed away from other areas.

The modelling of seepage in IMARC 9 is briefly described in Sections 3.3 and 3.4 of EPRI (2007), but is described in more detail in Chapter 4 of EPRI (2002a). The relation used in the IMARC 9 model between net infiltration and seepage is taken from a U.S. DOE analysis. For any value of the percolation there are triangular probability distributions of seepage fraction and seepage flow rate.

Based on the U.S. DOE approach, EPRI (2002a) describes focused flow factors intended to represent a combination of spatial variability in the upper geological system, and uncertainty in the effect of localization of flow that approaches the repository drifts. Essentially, the relevant phenomena are captured by a "flow focusing factor, F", which is the ratio between the local flux in the wet areas and the average flux. US DOE has developed probability density functions for this flow focusing factor. In adapting these distributions to the discrete probabilities needed for the IMARC logic tree implementation, EPRI (2002a) integrated the distributions in order to define probabilities for when flow focusing is essentially non-existent and when it is substantial. The latter is represented by a focusing factor of 4 and the probability of this was found to be 0.135. When the flow is focused, the infiltration rate is increased by a factor of 4 over 25 percent of the area of the repository; the seepage rate for the remaining 75% of the drifts is set to zero, in order to maintain the correct groundwater flux. The flow is assumed to be unfocussed for all other cases (probability of 0.865).

Unsaturated flow can vary in time and, according to EPRI (2002a), unpublished U.S. DOE work suggests an "intermittency factor" ranging from 1 to 10,000. However, arguing that the geometrical reality of fractures considered in this work was unrealistic, combined with unpublished observations of seepage into the drifts, EPRI (2002a) omits this process and does not further discuss the possibility of episodic flows.

The model only describes seepage under temperate conditions. When the drifts are above boiling temperature, seepage is assumed to be impossible and the unsaturated flow is assessed to be directed around the drifts through the low temperature pillars. When the drifts are at sub-boiling temperatures, seepage and condensate flow are possible, but the rates are not modelled. These rates are not needed in the containment modelling because that only considers either 'wet' or 'dry' conditions. Wet conditions occur when sub-boiling temperatures are reached. Seepage becomes important only after containment failure – assessed to occur when drift temperatures have fallen into the temperate regime, when the IMARC seepage model is valid.

The IMARC implementation of the seepage model is based on look-up tables derived from the U.S. DOE analyses, assessed in EPRI (2002a). The continuous distributions obtained from the U.S. DOE analyses are discretized in a manner similar to other IMARC submodels.

IRT Assessment

The IMARC 9 seepage model is based on a critical assessment of U.S. DOE work in this area and appears to represent state-of-the-art. The EPRI model seems justified and not unnecessarily conservative. However, a few remarks are warranted regarding the clarity of the documentation.

Initially, it was not clearly presented how the different seepage assessments made by U.S. DOE are used together in justifying the EPRI IMARC model. Only after discussions with the EPRI

IMARC team, did it become evident that the model justification is based on the critical review of U.S. DOE reports presented in (EPRI 2000).

There is a need to expand the justification for omitting episodic flows. The fracture asperity argument presented in EPRI (2002a) is plausible, but does not provide sufficient evidence. The argument would be much enhanced if combined with observations from the existing drift at Yucca Mountain.

The handling of seepage during high sub-boiling temperatures needs better description. The IRT agrees that it is reasonable to omit this aspect from the model, because the containment model is not coupled to the seepage model, and because containment is containment is generally long-term (i.e. it is functioning well into the temperate region when the IMARC seepage model becomes valid). However, should either of these two conditions be invalid (e.g. by future updates of IMARC 9 or by new data on containment times), then it would be necessary to revisit the seepage model. The IRT, thus, recommends that this, as well as other critical assumptions, be clearly documented at an overview level. See also our general comment in Section 2.4. Our comments regarding handling of probability in general are given in Section 4.2.

3.4 Containment

Containment failure (i.e., a breach of the engineered barrier systems) would lead to the release of radionuclides from the wasteform. Containment failure encompasses several aspects including: corrosion processes, undetected initial defects and geotechnical issues.

3.4.1 Corrosion Aspects

IMARC Description

IMARC's EBSCOM code assesses the rate of failure of the components of the engineered barriers system (EBS). It includes models for the rate of failure of:

- The Cladding;
- The Titanium Drip Shield (DS);
- The Alloy 22 Waste Package Shell (WP) and Waste Package Closure welds.

Figure 3-2 shows the primary flow chart for the EBSCOM code that controls the execution of each realization of the logic tree. At the start of each realization, the value of the temperature for the formation of an aqueous phase (TAQ), the temperature-time profile, and the nature of the environment are either defined or selected from the appropriate distribution. Next, the initial state of each EBS component (i.e., drip shield, waste package outer shell, waste package outer and middle closure lid welds) is determined and the identity of any failed components (selected based on the defined initial failure frequency) is recorded. The time is then incremented and the temperature (re-)calculated. Once $T \leq TAQ$, the code proceeds to the DS and WP flow charts and the extent of corrosion damage is estimated for that time increment. Unless all of the EBS components have failed, the time is then incremented, the temperature re-calculated, and the extent of corrosion in the next time step estimated. This process is repeated until all EBS components of concern have failed, at which time the realization is stopped and the next realization is started. Once a particular EBS component has failed by a certain mechanism (or failure mode) (e.g., if the DS fails by Hydrogen-Induced-Cracking (HIC)), no further calculations are performed to determine failure time by other possible failure mechanisms (e.g., in this case, General Corrosion (GC)). Similarly, if the WP fails due to failure of the outer and middle closure lid welds, the calculation is terminated and the lifetime of the WP shell is not computed (no credit is taken for the WP 316NG stainless steel inner shell).

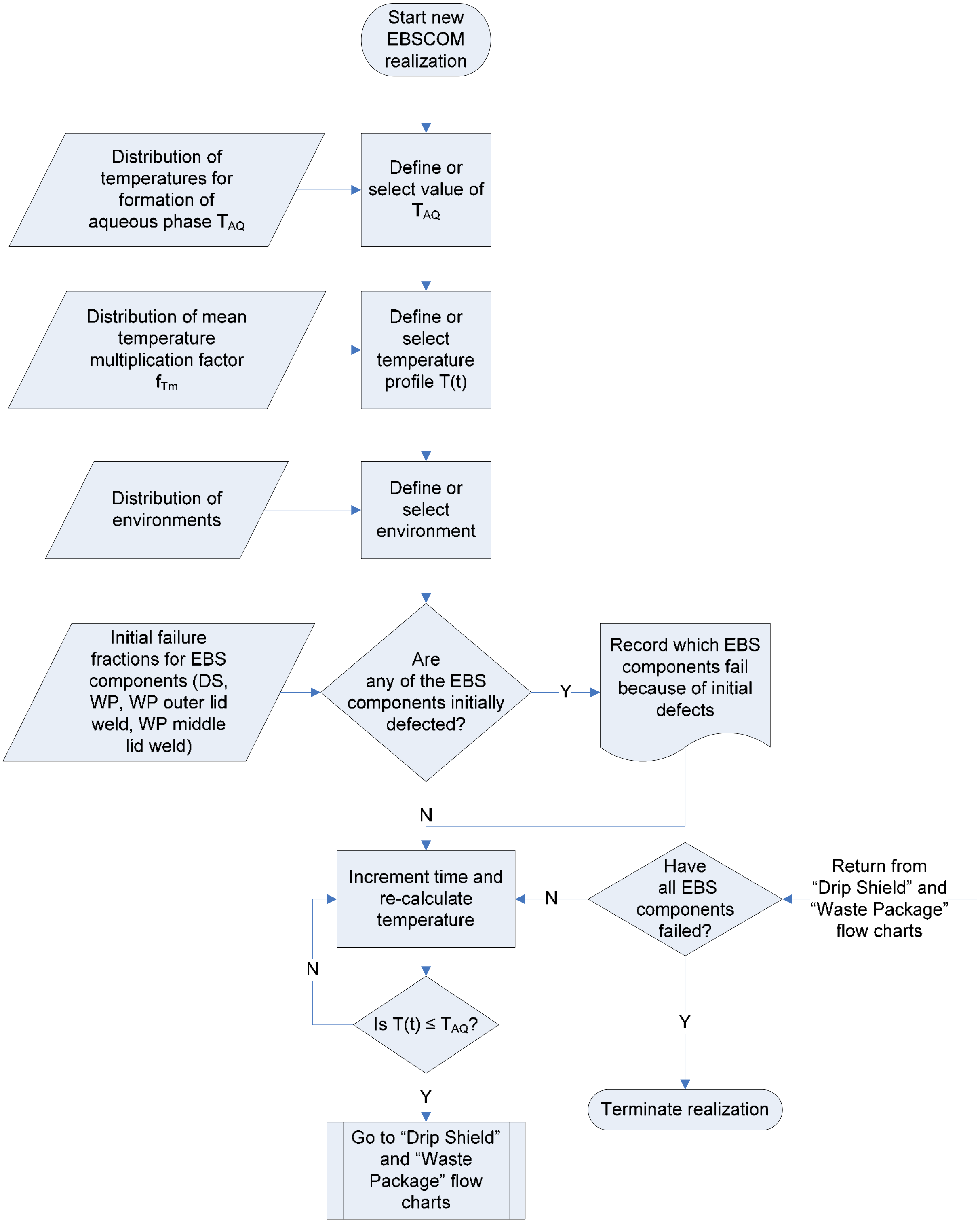

Figure 3-2
Overall IMARC 9 EBSCOM Corrosion Model (after EPRI 2007)

The Cladding

IMARC Description

The cladding failure model in IMARC 9 addresses the following modes of failure:

- Initial cladding failure – This is represented by a best estimate value of 2.44% of stored fuel rods, based on U.S. DOE estimates (EPRI 2000).
- Localized corrosion (LC) – This process (e.g. pitting in oxidizing saline conditions), is acknowledged in the text of the IMARC 9 draft report, but is not taken explicitly into account in the IMARC 9 model because the consequences of pitting failures are not expected to be significant, given that the apertures are expected to be small and at least partially blocked by corrosion products.
- General corrosion (GC) – This process is represented by general corrosion rates for wet and dry conditions.
- Hydride re-orientation – This process is neglected because cladding temperatures during the drying of higher burn-up spent fuels (prior to transfer from pool to dry storage) are limited to 400ºC. This operational limit ensures that little or no hydride re-orientation should occur.

IRT Assessment

The IRT concurs that relevant failure mechanisms are addressed in the IMARC 9 description of the cladding failure model and supports the consideration of the cladding as part of the EBS in IMARC 9.

Furthermore, the IRT concurs with the argument that LC (e.g., pitting) is unlikely to lead to a major exposure of fuel for dissolution. However, the IRT recommends that EPRI elaborates on the discussion in EPRI (2007) so that it provides the rationale for this argument, and shows that neglecting this process will not have a significant impact on the estimated dose.

The Drip Shield

IMARC Description

The drip shield failure model in IMARC 9 addresses the following modes of failure:

- GC – This is represented by a temperature-dependent Arrhenius expression. The modelling keeps track of the fraction of GC of the drip shield supported by the cathodic reduction of O_2, which does not result in hydrogen absorption (see Equation 3-1). This is important because it affects the probability of drip-shield failure by Hydrogen-Induced-Cracking (HIC).
- HIC – The corrosion of Ti is supported by the reduction of O_2 or H_2O:

$$Ti + O_2 + H_2O \rightarrow TiO_2 + H_2O \qquad \textbf{Equation 3-1}$$

or

$Ti + 2H_2O \rightarrow TiO_2 + 4H$ **Equation 3-2**

The corrosion of Ti by H_2O produces hydrogen atoms that can be absorbed by the DS and lead to hydrogen-induced cracking. Failure of the DS by HIC is deemed to occur once the absorbed hydrogen concentration reaches a critical value.

The rate of H absorption depends on a number of factors (Qin and Shoesmith 2003), including:

- the rate of general corrosion,
- the fraction of corrosion supported by the reduction of H_2O,
- the fraction of H produced by Reaction 3-2 that is absorbed by the oxide-covered metal (f_H), and
- the amount of absorbed H released from the matrix as corrosion proceeds.

As described above, the rate of general corrosion of Ti is given by an Arrhenius expression. Of this total corrosion rate, a fraction, f_{O2}, is assumed to be supported by the reduction of O_2 (Reaction 3-1) and a fraction $(1 – f_{O2})$ by the reduction of H_2O (Reaction 3-2). The fraction of the total corrosion supported by O_2 reduction will be a function of the drift environment. At elevated temperatures, the solubility of dissolved O_2 will diminish, an effect that may be compounded by the salting-out of O_2 in concentrated evaporates. At lower temperatures, the solubility of dissolved O_2 is higher, and a larger fraction of the overall corrosion may be supported by Reaction 3-1. For simplicity, in the IMARC model, the value of f_{O2} is assumed to be independent of temperature and the nature of the solution.

IRT Assessment

The IRT agrees that relevant failure mechanisms are addressed in the IMARC 9 description of the DS failure. Furthermore, the IRT considers that the approach to modelling GC and HIC in IMARC 9 is a reasonable approach.

In particular, absorbed H is assumed to be uniformly distributed throughout the DS. Preferential precipitation of H (as Ti hydrides) is observed during localized corrosion of Ti alloys in regions that are corroding relatively rapidly and for which the protective oxide film is thin or absent due to low pH in the pit or crevice. However, for general corrosion of the DS, the assumption of a uniform distribution of H is reasonable, given the relatively slow rate of H absorption compared with the rate of diffusion of H in the Ti matrix.

As discussed elsewhere (EPRI, 2002; Qin and Shoesmith, 2003), the assumption made in the EBSCOM code that all the H previously absorbed remains in the Ti matrix as corrosion of the DS continues is now believed to be overly conservative. The conversion of the Ti matrix to TiO_2 can be reasonably expected to release the absorbed H, which is then free to escape into the drift environment. In the EBSCOM code, therefore, it is assumed that some of the H already absorbed is lost as the Ti matrix is converted into TiO_2. Thus, at each time step in the realization, a fraction of the previously absorbed H is lost and a fraction of the freshly generated H is absorbed. The amount of H lost in each time step is assumed to be equal to the total in that amount of Ti metal corroded during the time increment. The IRT considers that it is reasonable to take account of the release of absorbed H as the Ti matrix corrodes and converts to TiO_2.

The Waste Package

IMARC Description

The waste package failure model in IMARC 9 addresses the following modes of failure:

- GC – This is represented by a temperature-dependent Arrhenius relationship. No enhancement factor is included to account for thermal aging. A factor is used, however, to represent the relatively lower rate of GC of the laser-peened closure weld on the outer lid. The GC rates are represented by a pdf derived using data from a 5-yr Long-Term Corrosion Test Facility (LTCTF) (CRWMS M&O 1999).
- LC – LC is assumed to initiate only under specific conditions and then to propagate at a certain propagation rate. LC initiation requires temperatures within a specific range and a specific water chemistry (i.e., the so called 'Bin 3 water' - see EPRI 2007). The lower and upper temperatures are specified as pdf's. If LC initiates, it is assumed to continue to propagate at a time dependent and temperature-dependent rate. The rate of propagation is assumed to decrease with time, essentially stifling LC growth after a certain period of time.
- Microbially Induced Corrosion (MIC) – The WP is susceptible to MIC when the temperature is below a threshold temperature. Therefore, MIC of the WP is potentially important in the long-term once environmental conditions in the drift have ameliorated sufficiently to allow microbial activity. One of the major stressors for microbial activity in the repository is the general lack of water, characterized by the low %RH in the drift. The RH is numerically equal to the thermodynamic water activity aW, a parameter that has been linked to the viability of different types of microbes (Brown, 1990; King *et al.*, 2004; Meike and Stroes-Gascoyne, 2000; Stroes-Gascoyne and King, 2002). Most microbial species are not active at aW < 96%, and this water activity has been proposed as a threshold value for the modeling of microbial activity in nuclear waste repositories (King *et al.*, 2004). The time dependence of the %RH (or aW) in the drifts is not explicitly included in EBSCOM but, as RH and temperature are closely linked, the conditions for the onset of microbial activity in the repository following the thermal pulse are defined by a threshold temperature for MIC, known as TMIC.

  Once active, MIC is represented in IMARC 9 through two factors that enhance the rate of GC and LC:

  - MIC-enhanced GC; and
  - MIC-enhanced LC.

  The MIC-enhanced GC is represented by a temperature-dependent enhancement rate. It applies to the waste package shell and the outer and middle closure lid weds.

  The MIC-enhanced LC is represented by enhancement factors of the LC rates of the outer and middle closure lid welds. There is no evidence of MIC-induced LC of Alloy 22.

- Stress Corrosion Cracking (SCC) – The WP shell and the non-closure lid are heat treated to relieve manufacturing stresses prior to loading of the spent nuclear fuel and so these components should not suffer SCC. However, once filled with the wasteform and sealed, the WP cannot be stress relieved through heat treatment. The surface of the outer closure lid weld can be stress relieved by laser peening or low-plasticity burnishing (Peters, 2003b), but there is a possibility, given certain conditions that SCC may affect the WP closure lid welds.

  In IMARC 9 SCC of the WP closure welds is modelled subject to several conditions:

  - the chemical environment must support SCC,
  - the value of the corrosion potential, ECORR, must be equal to, or exceed, the threshold potential for SCC, and
  - the tensile stress in the weld (σ) must exceed the threshold stress for crack initiation (σ_{INIT}).

  A fourth criterion for the SCC of the middle closure lid weld is that the outer closure lid must have previously failed, thus permitting an aqueous environment to contact the middle closure lid weld.

IRT Assessment

The IRT concludes that relevant failure mechanisms are addressed in the IMARC 9 WP failure model and that the components of the models are generally appropriate. For example, the IRT considers it reasonable to neglect the effect of thermal ageing on the rate of GC in Alloy 22. Some enhancement in the rate of Alloy-22 GC due to thermal ageing has been observed in boiling 50% H_2SO_4 + 42 g/L $Fe_2(SO_4)_3$, but tests conducted in more relevant environmental conditions indicate no enhancement (BSC, 2003, 2004e).

However, the draft IMARC 9 documentation (EPRI 2007) is not sufficiently clear on how surface stress is estimated or on how the model deals with cases where SCC is assessed to occur. The IRT suggests, therefore, that EPRI clarifies these points in its documentation, and that it should consider conducting a sensitivity analysis to assess the dose/risk importance of the IMARC 9 stifling model. If the stifling model is important, then the IRT recommends that EPRI provides further evidence to support the use of the stifling model under expected repository conditions.

Failures Caused by Initial Defects

IMARC Description

There is a very low probability that some EBS components placed in the repository may have significant initial defects. These defects would be either detectable faults missed by the inspection procedure, or undetectable, small faults located that might lead to premature container failure. Failure would occur when the full wall thickness of the EBS component (e.g., DS, WP, WP lid welds) was penetrated. Subsequently, irrespective of the size of the penetration, the EBS component is assumed to offer no further protection. A variety of initial defects, depending on their type (crack, void, inclusion, etc.), position (weld, sidewall), and size, can be expected.

Some of these defects may lead to rapid failure, whereas others would require some time to grow before perforation occurred.

IRT Assessment

The IRT concurs that the consideration of initial defects in the containment model makes sense. The assumption of complete failure regardless of defect size is clearly conservative. Regarding documentation of the model in the IMARC 9 report, the IRT had difficulty understanding what specific probability was used for initial defects and what it was based on. For perspective, in the Canadian EIS (AECL 1996) and Third Case Study (Garisto *et al.,* 2004), the probability of critical defects being present was estimated by statistical analysis of failures of mass-produced products, such as pressure vessels and CANDU reactor pressure tubes. On the basis of these analyses, Doubt (1984, 1985) has estimated that between 1 in 10,000 and 1 in 1,000 containers would contain defects capable of causing early failures.

At present, there is little information upon which to base a prediction of failure times for EBS components with such defects. However, EBS components with the largest defects might be expected to fail almost immediately, whereas those with smaller defects should require some time before failure. It has been assumed that these failures follow a simple ramped distribution with the largest number of defective containers failing at $t = 0$ and all failures being complete after a short period of time.

In the Canadian program, the actual number of containers failing prematurely in a given sector of the repository was determined by sampling from the binomial distribution for N trials, each with a probability, p, of failure, where N is the number of containers in each sector and p is sampled from a lognormal distribution. The lognormal distribution for p was chosen to have a geometric mean of 2.0×10^{-4} failures per year and a geometric standard deviation of 1.5 and 2 (for the EIS and Third Case Study, respectively). The distribution was truncated at a lower value of 10^{-4} failures per year and an upper value of 10^{-3} failures per year to reflect the information compiled by Doubt (1984, 1985).

<u>Rock Mechanics Aspects</u>

IMARC Description

IMARC 9 considers rock fall resulting from drift degradation and thermal stresses as part of the nominal scenario. The possibilities for such rock fall are assessed in EPRI (2006b), using both EPRI and U.S. DOE analyses. EPRI (2006) concludes that U.S. DOE's Drift Degradation Analysis and Modelling Report (BSC, 2004) does a thorough job of analyzing drift degradation due to thermal loading, seismic events, and time-dependence. Furthermore, supplementary EPRI numerical analyses were conducted using UDEC, a two-dimensional code produced by Itasca (UDEC, 2006).

The results of EPRI's UDEC analyses were assessed by looking at the damage within the rock mass and at the amount of rock that dislodged and fell from the roof or walls. Two formulae for stress corrosion were investigated, a power-law formula and an exponential formula. Even though the two formulae predict the same crack growth when analyzing laboratory crack growth data, when extrapolated to very low crack velocities that could impact over a one million year time-scale, the two formulae predict very different results. EPRI (2006) concluded that the exponential formula (without a lower bound cut-off) is unrealistic at low values of stress intensity. This exponential formula was, thus, not used in producing the final results for use in TSPA (see EPRI 2006).

IRT Assessment

Overall, the IMARC approach follows that of the U.S. DOE. The IRT notes that the U.S. DOE approach and the subsequent EPRI analyses seem to be state-of-the-art.

3.5 Radionuclide Release from the Engineered Barriers System

The source-term model in IMARC 9 calculates the release rates of selected radionuclides from spent fuel upon containment and cladding failure, and contact with water. The list of selected radionuclides has been developed by a screening procedure (see Section 3.5.1). Other components of the source-term model include:

- instant and congruent release models (Section 3.5.2);
- wasteform degradation model (Section 3.5.3);
- element-dependent solubility limits (Section 3.5.4).

The release of radionuclides from the EBS and into the UZ is also affected by mass transport through the EBS and the EBS-UZ interface. This is discussed in Section 3.5.5.

3.5.1 Radionuclide Screening

IMARC Description

IMARC 9 tracks the release and migration of the following radionuclides: Tc-99, I-129, Th-229, U-233, U-234, U-235, U-236, Np-237, U-238, Pu-239 and Pu-240. This set of radionuclides has been selected by EPRI based on a screening assessment.

IRT Assessment

The radionuclide screening assessment is not included in the IMARC 9 report (EPRI 2007) or in other documentation available to the IRT and, thus, it has not been reviewed.

The IRT notes that other radionuclides, including Cl-36, Se-79, Ra-226 and its progeny, are explicitly modeled and have sometimes been shown to be potentially important in assessments of spent nuclear fuel disposal made by other waste disposal programmes.

The IRT recommends that EPRI documents the radionuclide screening assessment within the IMARC 9 documentation. EPRI is also recommended to provide an estimate of the fraction of the RMEI dose attributable to the radionuclides included within the assessment.

3.5.2 Instant Release

IMARC Description

Following EBS failure, radionuclides may be released from spent fuel by several mechanisms:

- gap inventory release;
- grain boundary inventory release;
- matrix inventory release.

The gap inventory comprises the radionuclides on the outside of the fuel pellets that are directly accessible for dissolution upon contact with groundwater. The matrix inventory comprises radionuclides incorporated within the fuel pellets in a solid solution with the UO_2-phase. It is generally assumed that these radionuclides will be released at a rate which is proportional to the alteration and degradation rate of the UO_2 matrix. The grain boundary inventory is of an intermediate accessibility, as radionuclides have to diffuse through the network of grain boundary pore-spaces before reaching, e.g., the groundwater in contact with the fuel.

In the IMARC 9 model, the release of both the gap and grain-boundary inventories are represented through the use of a single instant release fraction (IRF). No credit is taken for the presumably slower release of radionuclides deeply embedded in the grain boundaries of the fuel pellets. The matrix inventory is assumed to be released at a constant release rate due to a constant matrix degradation rate until the whole inventory is depleted (see Section 3.5.3).

IRT Assessment

The IRT considers that the IRF model in IMARC 9 is conservative. The combination of gap and grain boundary inventories in the model will cause an overestimate in early dose rates (but probably of less than an order of magnitude). Improvement of the grain boundary release model to make it less conservative and more realistic would require a major effort. The current IRF model is, therefore, considered to be adequate. It is noted that the performance advantages of a more mechanistic (e.g., surface area-dependent) grain boundary release model could be assessed by conducting a sensitivity analysis.

There is variability in IRFs related e.g. to burn-up and irradiation history. IMARC 9 uses single values to represent the IRFs. These values are conservative because the grain boundaries are included in the estimate. However, uncertainty and variability in the IRFs are neglected. In particular, the IRFs are considered to be constant with time. This approximation makes sense particularly because the overall degradation rate of the fuel matrix is assumed to be fast (see Section 3.5.3). Several studies have addressed the potential ongoing segregation of fission products in used fuel under dry conditions (SKI 2007; Olander 2004). This could result in an increase in the IRFs with time. However, even if ongoing segregation does take place, it is expected to be extremely slow (in particular, compared to the matrix degradation rate) and the present approach with constant IRFs is, therefore, justified.

The IRT recommends that EPRI includes a discrete section in the IMARC 9 documentation on the selection of IRF parameter values, their justification and the mathematical implementation of the instant release model.

3.5.3 Wasteform Degradation

IMARC Description

The release of radionuclides from spent fuel requires degradation of the EBS and access of water to the spent fuel container and wasteform. The characteristics of the Yucca Mountain system are such that water is not expected to contact the wasteform for over 10,000 years. Even if water did penetrate a breached container before 10,000 years, several characteristics of the system would limit radionuclide release:

- Some of the water would evaporate before it could dissolve and/or transport radionuclides.
- The water would have to penetrate the cladding.
- Many of the radionuclides are not very soluble in the repository environment.

However, spent fuel is assumed to undergo rapid alteration in the Yucca Mountain repository following waste package and cladding failure because of assumed oxidising conditions.

In the IMARC 9 model:

- Radionuclides bound within the spent-fuel matrix are assumed to dissolve into water congruently with spent fuel alteration.
- A constant spent-fuel alteration rate is assumed.
- Spent fuel alteration is characterised by a characteristic wasteform alteration time. This alteration time is uncertain, and is assigned assumed values of 1,000 years (probability of 0.05), 3,000 years (probability of 0.9) and 5,000 years (probability of 0.05).
- The concentration of certain radionuclides dissolved in water that accesses the WP is subject to solubility constraints.

IRT Assessment

The IMARC 9 model for waste degradation is formulated through the use of a wasteform alteration time. The IMARC 9 alteration time is based on a U.S. DOE model (BSC 2004), which estimates alteration times from a parameterization of once-through UO_2 and fuel dissolution studies (e.g., Stout and Leider 1998). This parameterization provides a dependence of the dissolution time on carbonate and oxygen concentrations, pH, temperature and effective surface area.

The IRT believes that both the U.S. DOE and the IMARC 9 alteration times are very conservative for the following reasons:

- The dissolution rates were determined from once-through flow tests. As uranium concentrations in the surrounding solution increase, there will be smaller chemical and diffusive gradients driving dissolution.
- No credit was taken for the precipitation of alteration products, especially in the presence of Ca and Si. Although the absolute protective nature of such a precipitates is uncertain, they would be expected to at least partially block the underlying UO_2 surface and, thus, reduce the rate of dissolution.

The IRT recommends that EPRI continues current efforts to evaluate the applicability of more mechanistic spent fuel alteration models to Yucca Mountain conditions. In such a development it would be useful to continue to strike for a balance between unnecessary complexity and essential mechanistic features. The used fuel alteration model could incorporate the effect of radiolysis, temperature, redox conditions, pH and water chemistry on the fuel dissolution rate. It could also include precipitation of U(VI) phases as a function of these parameters and their evolution into progressively more stable forms. The critical aspect in such a model would be the definition of conditions (if any), under which the alteration products adhere to the used fuel surface in a manner which blocks or slows dissolution. It should be noted that if the alteration model results in significantly slower dissolution rate, it would be important to revisit the IRF model and evaluate the adequacy of the grain boundary release assumptions.

3.5.4 Element-Dependent Solubilities

IMARC Description

The IMARC 9 model assumes that the concentrations of dissolved radionuclides cannot exceed their element-dependent solubilities. Element-dependent solubilities are treated as uncertain parameters.

The IRT has not reviewed the consideration of colloid formation and transport in IMARC 9. The IRT focused its review of element dependent solubilities on Np-237, because of its potential major contribution to the RMEI dose (due to its long half-life of 2.14 x 10^6 years, potential mobility in oxidising conditions, and radiotoxicity).

Several models appear in the literature for assessing solubility limits of Np at the surface of dissolving spent nuclear fuel under the Yucca Mountain conditions. These include:

a) A model based on the solubility of crystalline Np_2O_5. This model is highly conservative with respect to data obtained from spent fuel leaching and drip experiments (Chen *et al.,* 2002; Friese *et al.,* 2004). This Np(V) phase has a solubility of about 10^{-5} M Np in repository groundwater (Friese *et al.,* 2004).

b) A model assuming that maximum Np concentrations can be determined by the solubility of crystalline NpO_2. This model is based on the evidence that crystalline NpO_2 is thermodynamically more stable than crystalline NpO_5 in the repository environment (Roberts *et al.,* 2003). This model is also conservative with respect to Np concentrations in spent fuel leaching experiments which are typically in the range of 10^{-10} to 10^{-8} M.

c) A model assuming that Np concentrations are determined by the (co-)precipitation of Np in a solid solution with secondary uranium minerals. The estimated concentrations using this model are in good agreement with experimental evidence such as long-term drip experiments. These concentrations are typically 2-4 orders of magnitude less than the solubility of crystalline Np_2O_5, and 1-3 orders of magnitude less than the solubility of crystalline NpO_2.

The IMARC 9 model assumes that Np co-precipitates with secondary uranyl minerals in which Np(V) substitutes for U(VI), with a charge balance maintained by substitution of divalent alkaline earth cations by H^+ or monovalent alkali metal cations (i.e. model (c)).

IRT Assessment

The IRT agrees that use of an Np co-precipitation model is a reasonable approach and that it is consistent with empirical data (e.g., Wilson and Bruton 1990; Wilson 1990a, b), but notes that such a precipitate has not been directly identified in dripping experiments under Yucca Mountain repository conditions.

Studies that support EPRI's source term model (directly or indirectly) show that Np(V) can be incorporated in a solid solution with uranyl minerals (e.g. Fortner *et al.,* 2004; Burns *et al.,* 2004; Burns and Klingensmith 2006) and this suggests that such phases could form as alteration products of used fuel.

The IRT notes that Schuller *et al.,* (2007) have used quantum-mechanical calculations to determine the energetically most favourable Np(V) incorporation mechanism (e.g., charge balance process) into uranyl phases.

Having noted that the use of a Np co-precipitation model is reasonable and probably more realistic than a model based on pure Np phases, the IRT believes that the consideration of schoepite as an end-member of the assumed solid solution (rather than more stable U minerals such as uranophane) is conservative.

A more conservative co-precipitation model would assume co-precipitation of an amorphous (non-crystalline, meta-stable) solid, but over time it would be expected that there would be a progression from amorphous to more crystalline solid phases. This progression is likely to be a complex kinetically-controlled process.

Thus, the IRT notes that there is some uncertainty surrounding the precise nature of the solid precipitate and because of this the IRT recommends that EPRI carries out a sensitivity analysis to explore the effect of uncertainty in the value of Np solubility on the overall dose results.

3.5.5 Radionuclide Transport through the EBS and UZ Interface

IMARC Description

In IMARC 9, mass transport through the EBS is modelled using the COMPASS code. IMARC 9 only describes the COMPASS and COMPASS-UZ interface in general terms. A detailed description of this interface is provided by Wei (2007).

The radionuclide release rate from COMPASS is given by the advective flux plus the diffusive flux calculated assuming a zero outer concentration boundary condition. In order to provide input to the unsaturated zone code, which has been implemented with a concentration boundary condition at the upper edge of the unsaturated zone solution domain, the output from COMPASS is translated into a concentration boundary condition using the average advective flow into the unsaturated zone:

$$C_i = R_i / vA, \qquad \textbf{Equation 3-3}$$

where R_i is the release rate from COMPASS (mol/y), v is the infiltration rate outside of the shadow zone of the drift (m/y), and A is the cross sectional area of the repository (m^2). This simple approach will tend to underestimate concentrations at the interface between the near field and the unsaturated zone, but ensures consistency in the total mass flux between COMPASS and the UZ model.

An additional complication to the use of COMPASS arises owing to the multiple release mechanisms from the spent nuclear fuel containers. At each interval in time in the performance period, IMARC evaluates the fraction of waste packages that have failed in the dripping and non-dripping parts of the repository, and conducts an analysis for both of those conditions. Radionuclides contained in the gap and grain boundary fraction are released immediately upon waste package failure, so COMPASS must be run at each time step (in the distributed container failure curve), to evaluate the releases from waste packages that have failed during that time increment. Therefore, at each time step, COMPASS is run for dripping and non-dripping conditions, and the resulting releases are added to releases occurring at that time from waste packages that failed at all previous time steps. The result is the cumulative release from a set of waste packages that have failed by different mechanisms over different time scales. Therefore, at any time, the summed releases represent the total release (mol/y) from all waste packages that have failed prior to that time.

IRT Assessment

The applied boundary conditions in COMPASS and the UZ model ensure continuity in mass. As pointed out by the IMARC team, the approach of prescribing the input mass flux to the UZ may tend to underestimate concentrations at the interface between the near field and the unsaturated zone, but since it ensures consistency in mass flux between COMPASS and the UZ, it is appropriate. As discussed in Section 3.7, the geosphere codes in IMARC are used to calculate the discharge rate (mol/y) at the accessible environment, using a standard 3,000 acre-feet/y dilution factor. Consequently, alternative approaches for calculating concentrations at intermediate points in the geosphere do not affect the concentrations at the accessible environment.

It appears to the IRT that dripping conditions in the near-field should be correlated to fracture flowing conditions in UZ, but this correlation could not be fully explored using a single UZ column - see Section 3.6. When the model was developed it might have been more realistic to use two different columns of the UZ model, where dripping sections discharge to a UZ column with high rate seepage and the non-dripping parts discharging to a diffusion-dominated UZ column. However, since the currently used UZ boundary conditions imply that migration through the UZ is dominated by seepage, using a single vertical column is justified.

The IRT encourages the detailed documentation of COMPASS recently undertaken by EPRI and recommends that it is included in the IMARC 9 document. In addition, it is recommended that EPRI provide an Assessment Model Flowchart (AMF) that gives an overview of IMARC 9 and its various sub-models.

3.6 Unsaturated Zone Flow and Transport

IMARC Description

The IMARC 9 model of the unsaturated zone (UZ) could be used to represent several one-dimensional vertical columns allowing approximation of the spatial variations of repository releases from the repository horizon. However, in its current implementation only one column is used. It is assumed that the flow and the transport of the radionuclides are directed downwards only. The one-dimensional columns can be represented either as a single-porosity, single-permeability or double porosity/double permeability medium thus describing the coupled matrix/fractures interactions.

The vertical variations are depicted by introducing stratification for several flow and transport parameters in each of the vertical columns. These variations include:

- variations in the initial moisture or introducing equilibrium gravity drainage;
- variations in permeability, capillary pressure and porosity and fracture spacing in each rock strata for both the fractures and the matrix;
- bulk density data and fracture spacing in each geological layer;
- time-dependent infiltration rate and radionuclides fluxes used as flow and transport boundary conditions at the top of the vertical columns; and
- dispersivities, decay factors, diffusion and sorption coefficients under linear Freundlich isotherms for each radionuclide.

The UZ code numerically solves the flow and the transport equations for the fractures and the matrix using a finite-volume technique and finite-difference approximation with application of a full Newton iteration with variable substitution, using either pressure or saturation as a primary variable (EPRI, 1996, Section 7.5).

The current IMARC implementation of UZ only considers a single vertical column. The vertical stratification of the unsaturated zone is represented as six overlying segments:

- The first segment consists of one finite difference cell only, which is used to specify the boundary conditions for the water in-flow and radionuclide fluxes from the near field;
- The next four segments are used to represent different unsaturated horizons below the repository: TSw-3C, TSv-5, CHnv-5, and CHnz-6;
- The last segment consists of one cell only situated below the water table and used as a boundary condition to fix pressure.

Among the most important parameters for the unsaturated zone are the characteristic curves, expressed in IMARC as saturation versus air entry pressure and saturation versus relative conductivity. These, and other input data are taken from the work of the U.S. DOE.

IRT Assessment

The IMARC model of unsaturated flow appears to be state-of-the art and allows exploration of the sensitivity of the system to the different hydraulic and migration processes that may be active in the unsaturated zone. The simplification to one-dimensional transport appears justified – and its justification has also been explored by sensitivity analyses.

The IRT notes that it should be recognized that the unsaturated flow is likely to be dramatically different if the upstream boundary condition is high rate seepage rather than diffusion dominated. In the former case, migration would be controlled by the fractures and travel times could be short, whereas in the latter case, the flow and migration through the rock matrix is a slow process. This needs to be recognized when implementing the code in IMARC and when selecting parameter values.

In this context, the IRT was originally concerned about the use of a single vertical column, since this, in general, would not sufficiently represent the spatial variability of the rock properties. Furthermore, this important limitation was not evident from the IMARC 9 documentation, but was clarified during the meetings with the IMARC team. However, the IRT accepts the argument provided by the IMARC team that given the current boundary conditions, migration though the UZ is dominated by seepage, therefore, the remaining spatial variability in migration properties is of relatively low importance. Consequently, using a single vertical column is justified. However, the IRT recommends that the IMARC document explicitly discusses this, and also generally remarks that the selection of a single vertical column is justified for the specified current properties and boundary conditions. See also our general remark in Section 2.4.

The mixed type boundary conditions used both for flow and transport at both the upstream and downstream side, allow for continuity and conservation of mass.

The input data assessment from US DOE data appears justified. However, more attention to the data abstraction process might be warranted in case the retention in the UZ was of a higher importance to safety.

3.7 Saturated Zone Flow and Transport

IMARC Description

The IMARC conceptual model for flow and transport in the saturated zone is one of fracture flow, but allowing for matrix diffusion and sorption in the rock between the flowing fractures (see IMARC 9, Section 6.2).

EPRI has assessed the US DOE approach of channelized flow or flowing intervals. A flowing interval is defined as a fractured zone that facilitates flow in the SZ. It is defined on the basis of borehole flow meter surveys. The flowing interval is characterized in terms of interval spacing, which is not the same as the fracture spacing. The flowing interval spacing is taken as the distance from the mid-point of the flowing interval to the midpoint of the next flowing interval. EPRI (2000) concluded that generally, flowing intervals cannot be correlated between boreholes. The connection among these zones along the flow system is inferred. EPRI (2000) further assumed that within the flowing interval, the fracture spacings and resulting block sizes will be much smaller than the flowing-interval spacing, and in keeping with fracture spacing measurements made from the SZ. This conceptualization was postulated in EPRI (2000) to be more realistic than the conceptualization used by US DOE, as it uses a flowing interval modeled as an equivalent hydraulic fracture with intervening rock between the flowing intervals considered as a rock block. EPRI (2000) postulated that representing the flowing zone as a fracture removes credit for matrix diffusion into the blocks along the flowing interval. This conceptualization remains the basis for flow and transport in the saturated zone in IMARC 9.

The SZ code is a general double porosity groundwater flow and transport code. The code is composed of two sub-blocks: one block for the water velocity field computation and one block for the radionuclides transport computation. However, in its IMARC 9 implementation, the SZ code has been used in a more restricted way, as described below.

In IMARC 9, it is assumed that the velocity field in the SZ is steady-state saturated groundwater flow in the fractures only. This is mainly due to computational constraints. The code has two options for the water velocity field to be introduced: as an initially given field, or as one to be computed under the boundary conditions specified for a specific run.

The flow boundary conditions in IMARC 9 are the spatially variable water inflow rate at the upstream boundary of the SZ computational domain, a temporally variable water infiltration rate at the bottom of the UZ column under the repository, and a constant infiltration rate over the rest of the water table. The boundary conditions for the transport equation consider no other dispersive boundary flux except one from the repository footprint, where the fluxes from the fractures and from the matrix for each of the vertical columns are incorporated as one; and boundary condition type III (Cauchy condition) is used over the entire water table surface.

Until 2003, the saturated-zone model in IMARC was implemented as three-dimensional, but based on sensitivity studies, the present IMARC 9 model uses a 2-dimensional representation of the saturated zone, which is set up as two segments: a fractured tuff segment extending from beneath the repository to 15 km down gradient, and an alluvial segment extending from 15 km down gradient to the location of the Reasonably Maximally Exposed Individual (RMEI) 18 km down gradient, the "compliance point", as established by US EPA.

EPRI (2000) noted that ground-water flow in the uppermost 200 m of the SZ is being carried in one-quarter of the vertical section. With the flowing intervals developed in this manner, linear flow velocities within the flowing intervals are four times higher than would be the case if flow were assumed uniform across the entire vertical section. Block sizes are determined based on the distance between flowing fractures within a flowing interval.

There is no direct coupling between the analyses of infiltration through the mountain to the repository, and those analyses considering infiltration in the far field. There are several computational constraints that require the net infiltration to be fixed to a constant value over the entire simulation period. Consequently, groundwater inflow at the upstream face, just upstream of the repository footprint, and the net infiltration rate over the water table of the saturated zone, are fixed at steady-state values throughout the analysis, thus defining steady state flow and constant water table depth. The values used are derived from US DOE analyses.

Regulatory requirements in the proposed 40 CFR 197 and 10 CFR 63 require an assumption of the use by the RMEI of 3,000 acre-feet of water per year (3.7×10^6 m^3/y). This value is called the "representative volume". In IMARC 9, the concentration of each radionuclide reaching the biosphere is typically calculated from the total discharge in the plume divided by the representative volume. IMARC 9 also contains alternative algorithms that can be used to calculate radionuclide concentrations reaching the biosphere if the flow in the plume were to exceed the representative volume, but these algorithms have been unnecessary in any calculations to date because of the low values of transverse dispersivity used.

IRT Assessment

The IMARC 9 conceptual model appears consistent with the US DOE assessment of the saturated zone, but the resulting retention offered by the saturated zone depends critically on the assumed boundary conditions (particularly infiltration at the top surface and the inflow rate at the upstream boundary), block size, flow "focusing" (caused by the flowing intervals), matrix diffusivity, and sorption. The IMARC interpretation of flowing intervals could reduce some unnecessary conservatism in the US DOE approach. However, the IRT has some remarks regarding the IMARC conceptual model.

The IRT agrees that it is correct to only consider the flow over the flowing intervals, and increase the flux in the SZ by dividing the average flux by the percentage of the vertical profile representing flowing intervals. This will increase flux over the remaining vertical profile and reduce the importance of matrix diffusion.

The IRT also agrees that block sizes should be determined by the distances between flowing intervals, rather than the distances between the flowing fractures within the flowing intervals, as the latter would be unnecessarily conservative. As EPRI concludes, with large blocks, diffusion into the matrix is likely less effective in attenuating the rate of spread of contaminants than would be the case with smaller blocks. Conceptualizing the SZ in terms of flowing intervals with rock blocks determined by the fracture spacings makes matrix diffusion more viable as a mechanism to attenuate the rate of contaminant migration. However, the IRT notes that basing the block size on the fracture spacing is strictly only valid for the case when the flow is equal in all fractures and flowing intervals. In the case of uneven flow between fractures, the effective block size is a function of the distance between the fractures carrying most of the flow. This should be better acknowledged in the IMARC documentation.

Furthermore, while the applied boundary conditions for flow and transport are generally justified, it should be noted that flow and, thus, retention, in the saturated zone will depend critically on the assumed inflow rate at the upstream boundary of the SZ computational domain and on the constant infiltration rate assumed over the rest of the water table. This should be better acknowledged in the IMARC documentation.

Although the SZ code has not been reviewed extensively by the IRT, the SZ code appears fit-for-purpose. Furthermore, the sensitivity tests carried out fully support the reduction to two-dimensions – and possibly even to a one-dimensional solution - given the fact that the current biosphere endpoint makes transverse dispersion a non-issue.

As noted above, the assessed ability of the saturated zone to retard radionuclide transport depends on the assumed boundary conditions and parameter values used (e.g., for block size and flow "focusing" caused by the flowing intervals, matrix diffusivity, sorption). While most parameter values are taken directly from the US DOE assessment, the IMARC team derives the used block size independently. Basing this on the distance between flowing fractures inside a flowing interval is strictly correct only if the flow is relatively evenly distributed between these fractures. IRT recommends that EPRI enhance the documentation justifying the selection of these critical inputs.

The approach used within the IMARC 9 model for calculating radionuclide concentrations at the compliance point appears to be consistent with the regulations.

3.8 Biosphere

IMARC Description

In the IMARC 9 TSPA code, the biosphere is represented using a set of input parameters, known as Biosphere Dose Conversion Factors (BDCFs). To calculate dose to the RMEI, the BDCFs are simply multiplied together with the assessed concentrations of radionuclides in groundwater at the compliance point.

EPRI's BDCFs are calculated using the computer code AMBER, Version 4.5 (see Enviros and Quintessa 2003; Enviros 2003), which implements a detailed biosphere model, first fully documented in EPRI (1996b) and subsequently revised and updated through until EPRI (2007).

The detailed biosphere model was developed by systematically considering potentially relevant FEPs and using matrices to identify FEP-FEP interactions that might influence radionuclide transfers between different biosphere compartments, or entities (e.g. water, soil, crops, food). Potentially significant radionuclide transfers between biosphere entities in the current version of the model are represented in AMBER as a set of linear algebraic equations and related parameter values (EPRI 2007 Appendix B).

In IMARC 9, a detailed biosphere model has been used to derive BDCFs for 12 key radionuclides (Tc-99, I-129, Th-229, Th-230, U-233, U-234, U-235, U-236, Np-237, U-238, Pu-239, Pu-240). EPRI's Biosphere model is a compartmental model and includes the following exposure pathways (EPRI 2007):

- Drinking of domestic water;
- Bathing in domestic water;
- Inhalation of soil and other dust suspended in air;
- Inhalation of irrigation water;
- Incidental ingestion of soil;
- External exposure to soil;
- Ingestion of food products, including crops (root and green vegetable, grain and fruit) and animal products (beef, chicken and eggs).

This compartment model is used separately from IMARC to calculate a set of BCDFs, which are used as inputs to the IMARC TSPA calculations. Key data sources used include Wasiolek (unpublished) for habit and food consumption data and IAEA (2003) for certain other parameters.

IRT Assessment

EPRI's overall approach to developing and justifying its detailed biosphere model is appropriate and consistent with international practice. The approach is also similar to that of the US DOE (US DOE 2007).

The equations that form the detailed biosphere model in AMBER and the data used are clearly and traceably presented and, in the vast majority of instances, the rationale for including or eliminating FEPs from the model is clear and reasonable. However, in more detail the IRT has several comments and observations, as follows.

Key Radionuclides. The IMARC 9 biosphere model considers fewer radionuclides than did previous versions of IMARC, and fewer than are considered in the US DOE model, which for example includes ^{14}C, ^{36}Cl and isotopes of Sr, Cs and Am. The IRT understands that the EPRI assessment team has undertaken a radionuclide screening analysis and has eliminated some radionuclides from consideration on the basis of importance. The IRT has not reviewed EPRI's radionuclide screening analysis, but recommends that EPRI includes in the IMARC 9 documentation at least a summary of the reasons underlying the selection and elimination of radionuclides (Section 3.5.1). While screening radionuclides from consideration based on their importance may be sensible, maintaining biosphere data for a wider range of radionuclides might provide some insurance for EPRI's TSPA against possible future US DOE changes to disposal system design that could mean that a different set of radionuclides becomes important.

Exposure Pathways. The IRT notes that the US DOE (2007) biosphere model includes a pathway that is not considered in the EPRI model, namely consumption of fish, farmed in radionuclide-contaminated water. The basis for the inclusion of this pathway in the US DOE biosphere model is that fish-farming is currently practiced in the Amargosa Valley (US DOE 2007). The IRT recommends that EPRI considers the potential significance of such a pathway.

Biosphere Transfer Model. IMARC 9 uses a K_d for modelling radionuclide retardation in soil. This is commonly the approach used in safety assessments. The IRT notes that at a rather detailed level, it is not always clear exactly which biogeochemical processes are actually represented by certain parameters in the biosphere radionuclide transfer equations. For example, the use of a K_d for modelling radionuclide retardation in soil may inevitably lump together several biogeochemical processes. For some radionuclides, such as Tc-99, this is a conservative approach because processes can occur in soils, such as biotic or abiotic reduction and co-precipitation (e.g., Abdelouas *et al.* 2005; Zachara *et al.* 2007), which might cause modelling approaches based on linear, reversible K_d values to underestimate retardation and overestimate radionuclide migration. Based on discussions with EPRI's assessment team, the IRT understands that the assessment team is aware of the possibility of pertechnetate reduction and that rather than using extreme parameter values, EPRI's TSPA deliberately uses values that have been selected from the middle of the possible ranges of K_d values and root uptake factors, as this is consistent with the *'reasonable expectation'* assessment context, and also avoids unrealistic combinations of extreme K_ds and root uptake factors. The IRT notes first, that these points could usefully be included in the IMARC 9 documentation and second, that EPRI should consider undertaking further analysis of the significance of uncertainties in biosphere input parameter values (see Parameter Uncertainty below).

Data and Parameter Values. The IRT has not been able to review all of the data used in the EPRI biosphere models, but has made some random spot checks to assess traceability and, where possible, to assess the appropriateness of certain parameter values. The IRT has found that the traceability of the data used in EPRI's detailed (AMBER) biosphere modelling is very good. Nevertheless, it would be useful to improve the IMARC 9 documentation and explain the reasons for change to the BDCFs that have occurred over the years. As to the appropriateness of the data on which the detailed biosphere modelling relies, it is noted, for example, that the recommended K_d for Th sorption to Yucca Mountain biosphere soils given in EPRI (2007) of 3 m^3/kg, falls within the range of 0.02 to 250 m^3/kg for all soils given in a recent review of biosphere parameter values (Thorne 2007) and, indeed, is close to the central value given in that review of 1.9 m^3/kg. Similarly EPRI's recommended values for Np animal product transfer factors also fall fairly centrally within the, albeit relatively wide, ranges of available data. EPRI's recommended values for these parameters appear reasonable but do not, on their own, capture the full range of parameter uncertainty; the treatment of parameter uncertainty is returned to below and in Section 4. With regard to data selection and the use of up to date data, it is noted, for example, that EPRI (2007) cites Ashton and Sumerling (1988) as the source of dose coefficients for external irradiation from soil, whereas more recent data may be available (e.g., US EPA 2002). The IRT recommends that, at an appropriate stage in its safety assessment process, EPRI reviews and updates its documentation and biosphere data as necessary.

Parameter Uncertainty. As noted above, EPRI's biosphere modeling involves a large number of parameters, many of which are uncertain. For example, animal product transfer factors and retardation coefficients may well vary over several orders of magnitude. IMARC 9, however, uses single BDCFs for each radionuclide. In 2004, EPRI explored the effect of parameter uncertainty on the resulting BDCFs through Monte-Carlo Analysis, in which each of the key uncertain parameters were sampled from probability density functions (Merino *et al.* 2004). In the Merino *et al.* (2004) analysis, the most important radionuclides were C-14, Tc-99, I-129, U-235, Np-237, Pu-239, Se-79, Cl-36 and Th-229 and the main exposure pathways were consumption of fruit, consumption of water, inhalation of dust, and consumption of eggs and cow meat. Merino *et al.* (2004) calculated cumulative distribution functions that showed a range of variation between one and two orders of magnitude for the BDCFs due to the variation of the input distributions. Although Merino *et al.* (2004) contains some useful results, it also appears to contain some conflicting statements, for example, as to whether the mean BDCF was higher than the median (50% percentile) BDCF for all radionuclides. The draft IMARC 9 report also seems to include some potentially conflicting statements; in some places it suggests that the BDCFs were derived using Monte Carlo analysis (IMARC 9, page 70), but in others this is not so clear (IMARC 9, page 174). It is, therefore, not exactly clear how the IMARC 9 BDCFs were derived, or whether they are mean, median or some other values. The IRT considers that EPRI should consider undertaking further analysis of the significance of uncertainties in the values of biosphere input parameters, should make clear exactly which BDCFs it is taking forward into TSPA (whether best estimates, distributions, means or other type of central value), and should present a clear justification as to why the values used in TSPA are consistent with its assessment context.

Linearity of BDCFs. As noted by IAEA (2001), the assumption that BDCFs are concentration-independent is not unreasonable for the trace quantities of radioisotopes that are likely to be released to the biosphere, but it may not be valid at higher concentrations. The IRT agrees with IAEA (2001) that TSPA and SZ model results should be checked to see if assessed radionuclide concentrations in groundwater reaching the biosphere could attain levels high enough to call into question the assumption that BDCFs are concentration-independent.

4

INTEGRATED MODEL AND INTERPRETATION OF THE RESULTS

IMARC 9 provides an integrated assessment of the total repository system and captures the main processes and their interactions. In addition to comments on specific model components (Section 3.0), the IRT considered several overarching issues related to the integrated model and the interpretation of the modelling results. Comments on these issues are provided in the following paragraphs.

4.1 Conservatism and Realism

IMARC Description

The EPRI IMARC methodology has tracked the evolution of Yucca Mountain regulations, disposal system design, and conceptual understanding of the proposed repository over the years. The IRT concurs that IMARC 9 is "fit for purpose" in the sense that it provides a risk-based methodology for integrating information from various disciplines affecting long-term repository performance, and focuses on a reasonable expectation of the dose consequence to the RMEI as defined by US NRC.

IRT Assessment

IMARC 9 is a very well integrated model, which focuses on those processes which are likely to affect the long-term performance of the repository. The US NRC 40 CFR 197 and 10 CFR 63 call for the performance of analyses that are consistent with a "reasonable expectation" philosophy as opposed, for example, to a "most conservative" philosophy. The IMARC code is generally consistent with the "reasonable expectation" philosophy and the applicable regulations, although some conservatisms remain in the IMARC model (e.g., the spent fuel dissolution rate, the modelling of instant containment failure, etc – see Section 3).

The IRT strongly supports the EPRI / IMARC studies on the deliquescent brines scenario (EPRI 2004b, Apted *et al*., 2006). These studies show that such brines are unlikely to form or cause LC, even if they formed and were stable. Although the IRT has not reviewed deliquescence in great detail, it seems reasonable, on the basis of these studies (EPRI 2004b, Apted *et al*., 2006), to eliminate deliquescent brine formation and the consequent early failure of WPs by LC from the assessment.

The IRT recommends that EPRI continues to study ways to move away from overly conservative assumptions towards more scientifically credible and realistic assumptions. This is important, particularly for risk-sensitive processes. For example, if a sensitivity analysis shows that the spent fuel dissolution rate in IMARC 9 is risk sensitive over a given time-frame, it would be useful to study the availability of data and the feasibility of developing a less conservative, more mechanistic fuel alteration model for the time period of interest. The IRT supports an initiative in this regard, currently being undertaken by EPRI, which includes looking at the potential development of a protective layer on the surface of the spent fuel during its degradation. This could be an important effect and will require careful consideration.

4.2 Treatment of Uncertainty

IMARC Description

Uncertainty is addressed in IMARC using two different methods. The primary method of uncertainty propagation uses the logic tree approach. In this approach, parameters are specified as high, moderate, and low values with probabilities associated with each. For instance, the moderate value of the parameter may be assigned a probability value of 0.9 (see Figure 3.1) with the high and low ends of the parameter range each assigned a probability of 0.05. It is necessary for the probabilities of values for a particular parameter to sum to unity. In some cases, this triangular distribution is replaced by a high-low value set, with only two values of associated probabilities. The event tree approach identifies each permutation of the parameters, propagates the associated probability of the combination of branches, and assigns probabilities to each branch end member.

The second method of uncertainty propagation is based on Monte Carlo (MC) methods. MC analysis is used in the areas of EBS degradation and BDCF calculation to generate distributions (e.g. for waste package and cladding failure versus time; and individual radionuclide BDCF distributions) for use in the TSPA.

In IMARC 9, the following uncertain parameters are included in the logic tree:

- Infiltration rate - 3 branches reflecting high/moderate/low cases,
- Retardation values - 3 branches reflecting high/moderate/low cases,
- Spent fuel solubility/Alteration time - 3 branches reflecting high/moderate/low cases,
- Flow focusing factor - 2 branches reflecting no focusing and strong focusing, and
- Seepage fraction/Flow rate - 2 branches reflecting a base case and high values.

From the combinations of this set of uncertainty parameters, IMARC 9 derives the 3 x 3 x 3 x 2 x 2 = 108 calculation cases. All other parameters in IMARC 9 are treated as deterministic fixed values. However, as noted above, a number of the parameters used as input to IMARC 9 are really ‘lumped parameters’ derived through full consideration of the appropriate uncertainties and, in a number of cases, the results are derived using full MC based calculations (i.e. MC runs are performed outside of the IMARC 9 TSPA code to derive a statistic of the pdf for use in IMARC 9).

IRT Assessment

IMARC 9 treats uncertainty in conceptual models and individual model parameters by including uncertainty distributions in either a Monte Carlo (MC) approach (continuous uncertainty distribution) or via a logic tree (discrete values). Several scenarios are addressed by the code; the “nominal release” scenario is the most likely, and the one reviewed by the IRT.

MC is suitable for any type of input distribution, e.g. continuous or discrete (e.g. event-tree), provided the input distributions are correct. Thus, if an input distribution has 5% of one value, 90% of another value and 5% of the third value, this pdf can be incorporated into a MC framework without a problem. However, if the input distribution is an approximation of a continuous distribution then there could be some quantitative consequences to this approximation.

In the case where the discrete pdf is an approximation or simplification of a known probability distribution, the investigation of consequences depends on several factors

- the statistics of interest (e.g., mean, median, some particular upper percentile, etc);
- the functional form (e.g. adding or multiplying) of the model relationship;
- the relative/absolute variation in the discrete pdf compared to the other distributions. (if the range of the discrete pdf is small, e.g. 0.3, 0.4, 0.5, compared to the range of the other distributions, e.g., 0.01 to 10,000, then there will be minimal (inconsequential) effect. However, if the range of the discrete pdf is large e.g. 0.01, 10 and 10,000 compared to the range of the other distributions e.g. 0.3 to 0.5 then there will likely be consequential effects on many of the statistics.).

The event tree approach is an approximation to a full MC with continuous pdf’s. Overall, the IRT recommends that EPRI considers the development of a consistent approach to uncertainty analysis in IMARC that allows calculation of the mean dose that would be calculated from a full and thorough MC analysis. Possible steps towards this improved position could include (i) undertaking a careful analysis of the upper and lower parameter values assigned in the current IMARC 9 model and of the probabilities assigned to them, and (ii) carrying out sensitivity analyses to assess whether the approximation introduced by using discrete pdfs significantly affects calculated dose to the RMEI.

4.3 Sensitivity Analysis

IMARC Description

The IMARC 9 draft document focuses principally on the description of the IMARC model and its justification, and much less on the assessment results and their interpretation. Some sensitivity analyses are presented as part of the rationale for the development of some of the component models, but the consequences of the nominal evolution scenario are only shown in the IMARC 9 document for a best-estimate calculation case.

IRT Assessment

A sensitivity analysis is a quantitative examination of how the behaviour of a system varies with change, usually in the values of the governing parameters (IAEA 2000).

The IRT recommends that EPRI document the results of the IMARC 9 probabilistic assessment more fully (e.g., to illustrate the calculated performance of the various sub-systems and components of the EBS, and the associated uncertainties), and that it undertakes systematic sensitivity analyses with the aim of identifying which parameters contribute most to the uncertainty in the calculated total dose rates.

Sensitivity studies can be particularly useful for improving understanding of disposal system performance and prioritising future work to reduce key uncertainties and identify where the focus of effort should be when developing subsequent updates to the IMARC model.

To the extent possible, model uncertainties should be addressed within systematic sensitivity analyses. These sensitivity analyses could be based on risk insight from existing assessments and detailed modelling work, which could guide priorities towards risk-sensitive areas.

4.4 Code Inter-Comparison

IMARC Description

According to the draft IMARC 9 report, ongoing verification activities ensure that the code and its constituent parts are correctly implemented. The code is maintained under a configuration management system. Thorough testing is conducted of all changes implemented code, including benchmarking against analytical solutions and alternative computer codes, as appropriate.

IRT Assessment

The IRT concurs with EPRI's statement on the importance of code inter-comparison activities for the various sub-models that comprise IMARC 9. Such comparisons are useful for understanding assumptions and modelling approaches, as well as the effects of certain parameter values and data. Code inter-comparison is also important for understanding differences between different modelling approaches, and whether these differences are methodological or related to particular sets of parameter values. Once the differences are understood and resolved, the similarity between results obtained using different models can be used to enhance the scientific credibility of the models. The IRT recommends that EPRI also considers opportunities for comparing IMARC 9 with other TSPA codes.

4.5 System Understanding

IMARC Description

The overall conceptual approach that underlies the IMARC code and the elements it contains are outlined in Chapter 2 of EPRI (2007). The basic elements of the analysis method are claimed to be the same as in the most recently available version of U.S. DOE's TSPA (BSC, 2003). Differences between the implementation of IMARC and the implementation of U.S. DOE's TSPA code are in the details of and specifics of the assumptions, models, parameters, and couplings used.

Many of the US DOE models are incorporated in IMARC via either lookup tables or failure distribution curves. When IMARC deviates from the US DOE conceptual model or modelling approach, this is generally justified on the basis of an independent assessment of the issue and with a focus on processes of importance for system performance. The IMARC team generally only develops independent models in cases where comparison of the approaches suggests that a more realistic, less conservative approach than taken by US DOE could be justified.

IRT Assessment

Overall, IMARC appears to provide very good insight into the risk-important processes and elements of the Yucca Mountain disposal system. IMARC appears to have focused on the safety relevant elements of repository evolution.

The IRT understands that EPRI's system understanding and model selection are based on critical reviews of the US DOE work. Such reviews are documented in several EPRI reports. However, the IRT recommends that EPRI improve the overall documentation on the final judgements made based on these critical reviews. This would enhance traceability in how the IMARC code is justified – and would, thus, improve credibility.

4.6 Information Quality and Management

IMARC Description

Version 7 of the IMARC code was placed under a configuration management system in 2003. IMARC 7 has since undergone restructuring, first as IMARC 8 in 2005, and subsequently as IMARC 9 in 2007. The code structure for Versions 8 and 9 is described in Section 8 of the draft IMARC 9 report (EPRI 2007). Further code-related and quality-related issues are addressed in other sections of EPRI (2007), including Computer Code Benchmarking Activities (Section 1.3), the treatment of uncertainty (Section 2.7) and the verification of COMPASS (Section 5.4).

IRT Assessment

The IRT considers EPRI's use of a configuration management system for code development to be appropriate. EPRI is currently further developing its configuration management system to demonstrate even better control of code development activities – the IRT encourages EPRI to describe this work in the IMARC report.

In contrast to the obvious control over code development for the IMARC TSPA code, there appears to be no overall or systematic approach for assessing the quality of input data, or for data management. The adequacy of data is generally justified by giving reference to US DOE work and documents, but there is no pre-defined procedure for assessing and justifying input data. Although the IRT has found no specific examples of the use of unjustified data, the IRT recommends that EPRI consider making the use of suitable information quality procedures an integral part of conducting assessments with the IMARC code.

The IRT believes that it is important to justify all assumptions made and data used at each stage of IMARC development and use – even if only preliminary assessments are being made, or the assumptions and data may change in the future:

- The IRT notes that the justification for omitting specific processes or features from certain IMARC sub-models is sometimes based on the expected or actual output of other sub-models. For example, this is the case motivating that the seepage model does not consider the hot sub-boiling phase (see Section 3.3), and for motivating the use of a single vertical column in the unsaturated zone code (see Section 3.6). While such an approach is acceptable, there might be a risk that these interdependencies could be forgotten by individual team members when further developing a sub-model – or if there is an important change in input data or personnel. To mitigate this problem, the IRT recommends that EPRI should maintain a central record of modelling assumptions, including the reasons for FEP screening decisions.
- The IRT also recommends development of input data assessment procedures. These procedures should set out the ground rules for accepting input data for use in IMARC assessments.

5

CONCLUSIONS

IMARC 9 provides an integrated presentation of the total repository system and captures the main processes and their interactions. The IRT concurs that IMARC 9 is “fit for purpose” in the sense that it provides a risk-based methodology for integrating information from various disciplines affecting long-term repository performance and focuses on a reasonable expectation of the dose consequence to the RMEI as defined by U.S. NRC. IMARC 9 is a very well integrated model which focuses on those processes which could affect the long-term performance of the repository.

The U.S. NRC 40 CFR 197 and 10 CFR 63 call for the performance of analyses that are consistent with a “reasonable expectation” philosophy as opposed, for example, to a “most conservative” philosophy. The IMARC 9 code is generally consistent with the “reasonable expectation” philosophy and the applicable regulations, although some conservatisms in the IMARC models remain (e.g., the spent fuel dissolution rate, neglecting defect size in the modelling of instant containment failure).

The IRT recommends EPRI continues to study ways to move away from conservative assumptions (which are essential in the absence of sufficient data and full mechanistic understanding) towards more scientifically credible and realistic assumptions. This is important, particularly for risk-sensitive processes. For example, if a sensitivity analysis shows that the spent fuel dissolution rate in IMARC 9 is risk sensitive over the time-frame of interest, it would be useful to study the availability of data and the feasibility of developing a less conservative, and a more mechanistic fuel alteration model. The IRT supports an initiative by EPRI being undertaken in this regard.

Many of the IRT comments relate to improving the IMARC 9 documentation. Other comments provide suggestions for sensitivity analysis to identify which parameters contribute most to the uncertainty in the estimated dose rates.

The IRT also strongly supports ongoing verification and code-intercomparisons for gaining additional insight into the various assumptions and modelling approaches and for enhancing the scientific credibility of the model.

6

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A

SHORT RESUMES OF IRT MEMBERS

NAVA C. GARISTO

Nava C. Garisto is a manager of the Risk and Radioactivity group at SENES with over 25 years of scientific and consulting experience related to radiological risk assessment, pathways analysis, and safety assessment. Her particular interest is the development of risk-informed mitigation and management strategies. Nava Garisto has a Ph.D. in Chemical Physics and is the author of over 100 journal publications and reports in the radiological risk assessment field. She has developed and applied Multi-source, multi-pathways risk-assessment models for estimating human health and ecological impacts from both radioactive and chemical contaminants in operating nuclear facilities, radioactive waste sites, incinerators, spill sites and uranium mining and milling sites. These projects include studies in Canada, the U.S., and Europe.

Dr. Garisto is currently a member of the Canadian Standards Association CSA N288 Committee on modelling releases from nuclear facilities and N292 Committee on Radioactive Waste Management. She was a member of Environment Canada's Expert Review Group on risk assessment of radionuclides under the Canadian Environmental Protection Act; and formerly the program committee for the Materials Research Society on the Scientific Basis of Nuclear Waste Management in the U.S. She was also a member of the bi-national Sweden/Canada Committee on radioactive wastes and a Task leader of Performance Assessment under AECL/US DOE cooperation on Geological Disposal of Spent Nuclear Fuel. Examples of relevant studies that Dr. Garisto has directed include:

- Comprehensive safety assessment of a Deep Geological Repository for Low and Intermediate Level Waste in Ontario (including both radiological and chemical aspects for normal conditions as well as malfunctions and accidents);
- Development of a near-field model for the Post Closure Safety Assessment of Spent Nuclear Field Disposal in a Conceptual Geological Repository in the Canadian Shield, including: Spent fuel dissolution, source term modelling, container failure, mass transport, sorption, near field-geosphere coupling;
- Comprehensive ecological risk assessments at operating nuclear stations including: Pickering, Darlington, Bruce, Chalk River, Gentilly-2 and Point Lepreau;
- Risk assessments and risk management studies for sites with radioactive and chemical contaminants for the Port Hope and Blind River Cameco facilities and for uranium milling and mining sites.

JOHAN ANDERSSON

Johan Andersson is President of JA Streamflow AB. He has a Msc in Engineering Physics, a Ph.D. in Water Resources Engineering and a Dphil (docent in Swedish) in Hydraulics. He was part time professor in Engineering Geology at Chalmers Institute of Technology 1999-2003. After four years of post doctoral research on modelling flow and transport in porous media and crystalline rock he spent 6 years at the Swedish Nuclear Power Inspectorate managing, among other things, the inspectorate's integrated performance assessment projects and had a leading role in reviewing industry's research programmes. Since 1995 he has worked as consultant. Today Johan Andersson provides general advice on projects related to development and safety assessment of radioactive waste repositories and other installations with environmental implications. Clients include the Swedish Nuclear Fuel and Waste Management Co. (SKB), Posiva Oy Finland, Nuclear Waste Management Organisation of Japan (NUMO), Bundesamf für Strahlenschutz (BfS) and OECD/NEA. He has more than 18 years experience in assessing the Safety of nuclear waste repositories and on research related to hydrogeology and transport of radionuclides and other hazardous material in porous media and fractured rock. Among other things Johan Andersson is a technical coordinator between the site evaluation, Safety Assessment and Repository Engineering work in the SKB project aiming at a final repository for Sweden's spent nuclear fuel. He is chairman of the Posiva Modelling Task Force for producing integrated geosyntheses from the ongoing underground characterisation that would lead to a PSAR for the final SNF repository at Olkiluoto, Finland. He is also a member of the International Advisory Committee (ITAC) to NUMO, the nuclear waste management agency in Japan.

DAVID BENNETT

David Bennett is Director of TerraSalus Limited. He has over 15 years experience in providing strategic and technical consultancy advice on radioactive waste management and its regulation. He has a PhD in geochemistry, is a Fellow of the Geological Society, and has contributed to over 60 published papers and reports in the area.

Dr. Bennett's specialities include disposal facility authorisation and licensing, regulatory review and interpretation, risk and safety assessment, safety case development, engineered barrier systems, radioactive waste immobilization, and geochemical and radionuclide transport modelling. He has also contributed to a range of consultative optioneering / BPEO / options appraisals on waste management and disposal.

Dr. Bennett has contributed to radiological assessments and nuclear waste management programmes in Belgium, Finland, France, Germany, Japan, Sweden, the UK and the US, and has also contributed to several international programmes run by the European Commission, the International Atomic Energy Agency (IAEA) and the OECD Nuclear Energy Agency (NEA).

B
SCOPE OF WORK - IMARC CODE REVIEW

B.1 Workscope

B.1.1 Background

The objective of this task is to conduct a technical review of the Electric Power Research Institute's IMARC code (Integrated Multiple Assumptions and Release Code). This code has been developed by EPRI over the last 17 years as a tool for conducting independent probabilistic total system performance assessments (TSPAs) of the U.S. Department of Energy's (U.S. DOE's) proposed High-Level Radioactive Waste (HLW) Repository at Yucca Mountain, Nevada, USA. The TSPA will be a key feature of this anticipated U.S. DOE licence application for the candidate HLW Repository at Yucca Mountain. The TSPA models the evolution of the repository system of natural and engineered barrier systems (EBS) over many thousands of years, estimating the potential releases of radionuclides from the repository into the accessible environment.

EPRI has conducted independent TSPAs using IMARC to gain its own insight on important repository system features, events, and processes with respect to estimates of radiation dose to a hypothetical "reasonably maximally exposed individual" living downstream of the Yucca Mountain repository. These features, events and processes include: climate change, net infiltration, unsaturated zone groundwater flow focusing on groundwater seepage into the repository drifts, containment by drip shield, waste package, and cladding, wasteform dissolution, radionuclide solubilities, radionuclide transport through the unsaturated zone and saturated zone, and multiple exposure pathways in the biosphere. The IMARC code treats uncertainty in conceptual models and individual model parameters by a logic tree (discrete uncertainty values) formalism. Although the IMARC code was developed to address the "nominal release" scenario, more recent modifications of IMARC have been made to evaluate "natural event" scenarios such as igneous event or an earthquake event.

B.1.2 Tasks

Dr. Garisto shall be the chairperson of a three-person team contracted to provide an independent technical review of EPRI's IMARC code. The other participants are Dr. Johan Andersson and Dr. David Bennett. Dr. Garisto shall participate in an Orientation Meeting to be held in Washington, D.C., on the 6th and 7th of September, 2007at which details of the review shall be established. A report describing the IMARC code shall be made available to the Peer Review Team (PRT) a week before this orientation meeting, providing the core documentation for the review. Also at this meeting, the PRT will meet to organize their own review responsibilities and to establish a preliminary schedule for reviewing the various parts of the IMARC code.

The IMARC peer review shall include not only a review of the IMARC code documentation provided, but also a 1-2 day visit to the Monitor Scientific, LLC, offices in Denver, Colorado, USA to directly review / evaluate their assigned parts of the IMARC code. This visit will also allow the reviewer to interact directly with the various EPRI technical experts who developed the specific IMARC subroutines under review and to discuss any questions / concerns that might arise in the review. The target timeframe for his visit is late September through late October, 2007 and should be coordinated with Monitor Scientific LLC.

Dr. Garisto shall document her comments and recommendations with respect to the IMARC code and submit them to Dr. Andersson and Dr. Bennett for their review to ensure consistency in the review and to work out any review issues that might arise. In addition, Dr. Garisto shall document her comments and recommendations with respect to the IMARC code and submit them to Dr. Bennett for their review to ensure consistency in the reviews and to work out any review issues that might arise. In addition, Dr. Garisto will receive draft review comments from Drs. Bennett and Andersson for their of the IMARC code review. She will review their comments to ensure consistency in the review and to work out any issues that might arise. She will also use these draft comments to develop an Executive Summary of the entire IMARC peer review. The preliminary target date for this input to Dr. Garisto and for Dr. Garisto to submit her review comments to the other PRT members is 14 November, 2007.

Dr. Garisto shall prepare an Executive Summary of the independent review and submit this summary to Dr. Bennett and Dr. Andersson for their review and comment prior to submission of the Executive Summary to Monitor Scientific LLC. A final draft review report, which includes the Executive Summary and the individual PRT reviews, is due to Monitor Scientific by 17 December, 2007.

Dr. Garisto shall work with the PRT to resolve any questions on key comments / recommendations presented in the review report from Monitor Scientific and EPRI in accordance with procedures established at the orientation meeting, and a final review report shall be provided by 18 January 2008.

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